

OAET

SSTAC/ARTS REVIEW OF THE DRAFT INTEGRATED TECHNOLOGY PLAN (ITP)

Volume III: June 26-27

Space Power & Thermal Management

**Briefings from the
June 24-28, 1991 Meeting
McLean, Virginia**

**National Aeronautics and Space Administration
Office of Aeronautics, Exploration and Technology
Washington, D.C. 20546**

(NASA-TM-108652) SSTAC/ARTS REVIEW
OF THE DRAFT INTEGRATED TECHNOLOGY
PLAN (ITP). VOLUME 3: SPACE POWER
AND THERMAL MANAGEMENT (NASA)
321 p

N93-23109

Unclass

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SSTAC/ARTS REVIEW OF THE DRAFT ITP
McLean, Virginia
June 24-28, 1991

Volume III: June 26-27

Space Power & Thermal Management

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- PT8. High Capacity Power -- R.J. Sovie
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- PT11. Project SELENE -- John D.G. Rather

NASA

Space Energy Conversion Research and Technology

**INTEGRATED TECHNOLOGY PLAN
EXTERNAL REVIEW
26 JUNE 1991**

Gary L. Bennett

**Manager, Advanced Space Power Systems
Propulsion, Power and Energy Division
Office of Aeronautics, Exploration and Technology
NASA Headquarters**

AGENDA
POWER AND THERMAL MANAGEMENT
DISCIPLINE REVIEW

WEDNESDAY, JUNE 26, 1991

8:30 AM	ADMINISTRATORS REMARKS	R. Truly
9:30 AM	POWER OVERVIEW (90 min.)	G. Bennett
	<u>R&T BASE:</u>	
11:00 AM	PHOTOVOLTAICS (45 min.)	D. Flood
11:45 AM	CHEM. ENERGY CONVERSION (45 min.)	P. Bankston
12:30 PM	LUNCH (60 min.)	All
1:30 PM	THERMAL ENERGY CONVERSION (60 min.)	P. Bankston/ Calogeras
2:30 PM	POWER MANAGEMENT (90 min.)	Bercaw/W. Meador
4:00 PM	THERMAL MANAGEMENT (45 min.)	Swanson
4:45 PM	ADJOURN	

THURSDAY, JUNE 27, 1991

FOCUSED TECHNOLOGY:

8:00 AM	SPACE NUCLEAR POWER (60 min.)	J. Sovie
9:00 AM	HIGH CAPACITY POWER (60 min.)	J. Sovie
10:00 AM	SURFACE POWER & TM (45 min.)	J. Bozek
10:45 AM	EARTH-ORBIT PLAT. POWER & TM (45 min.)	R. Cull
11:30 PM	LASER POWER BEAMING (45 min.)	J. Rather
12:15 PM	LUNCH (60 min.)	All

SPACE ENERGY CONVERSION R&T

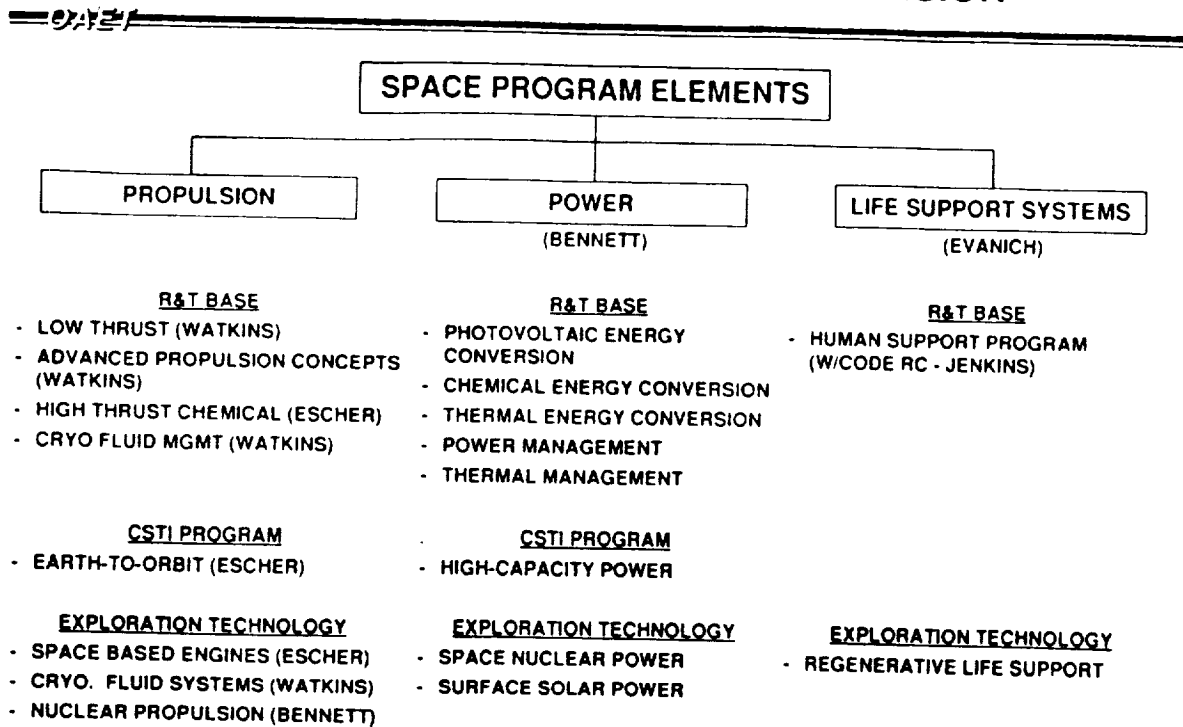
~~GA&T~~

ORDER OF PRESENTATION MATERIAL

- Work Breakdown Structure
- Space Power Technology
- Integrated Technology Plan Process
- Space Power Background
- Technology Needs
- Space Power Reviews and Studies
- Space Power Technology Development
- Coordination and Interfaces
- Budgets
- Summary
- External Review Process

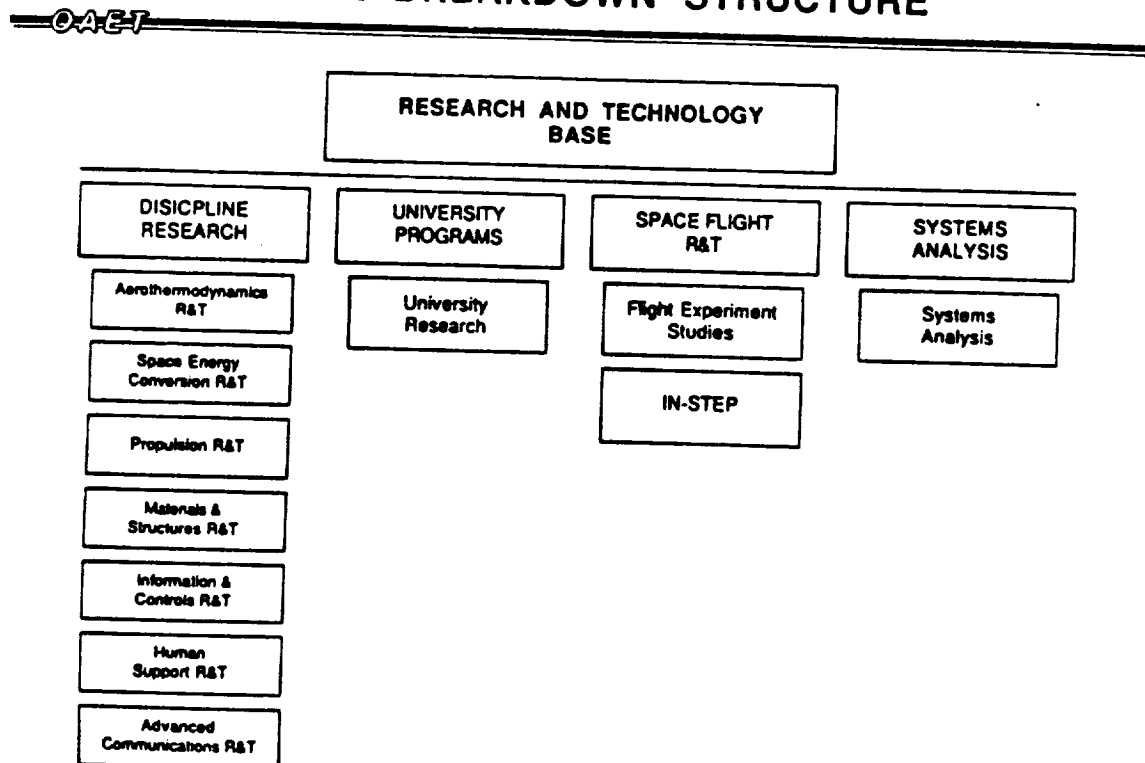
Work Breakdown Structure

PROPULSION, POWER & ENERGY DIVISION



FY 1991

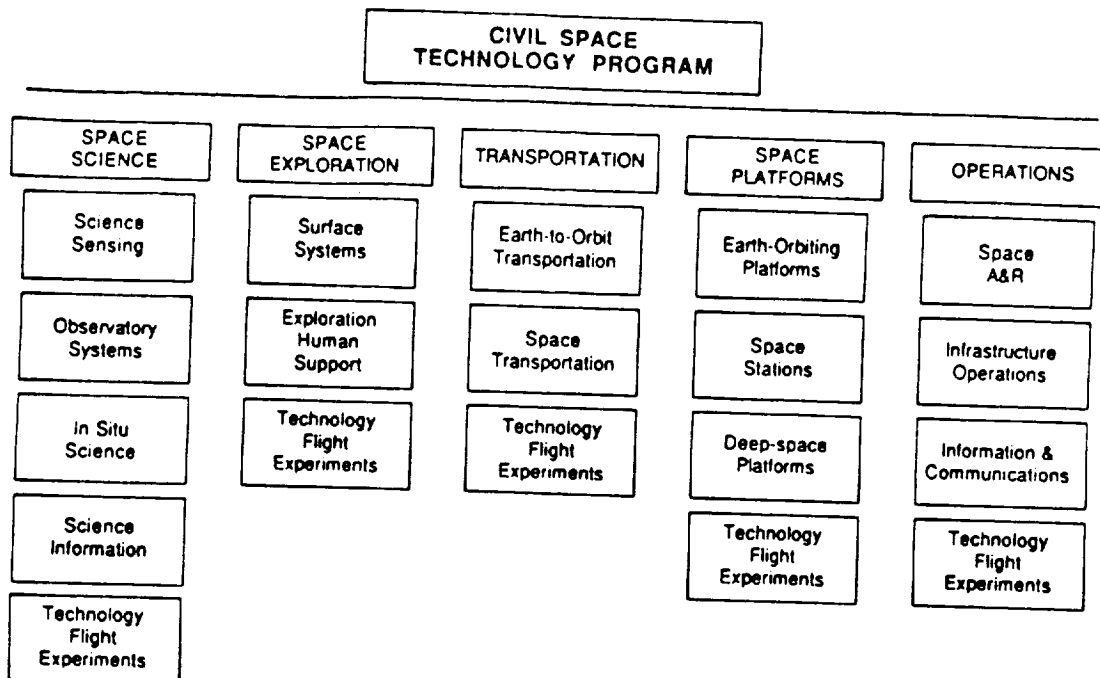
INTEGRATED TECHNOLOGY PLAN FOR THE CIVIL SPACE PROGRAM WORK BREAKDOWN STRUCTURE



MAY 16, 1991
JCM 7209

TECHNOLOGY PLAN FOR THE CIVIL SPACE PROGRAM WORK BREAKDOWN STRUCTURE

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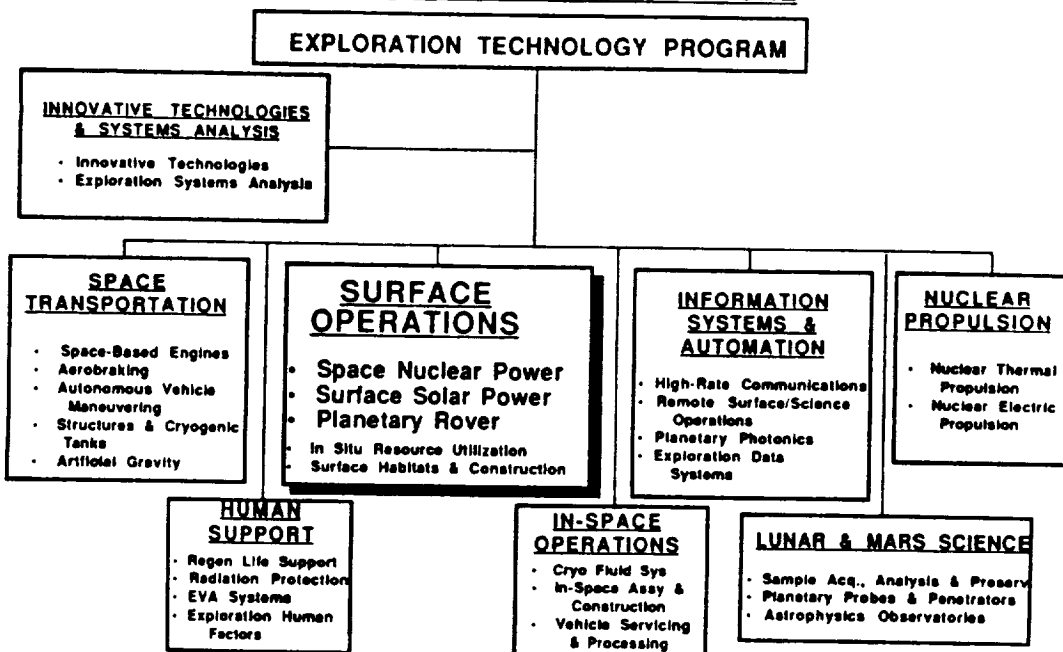
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JCM 7208a

NASA

EXPLORATION TECHNOLOGY

OAE

WORK BREAKDOWN STRUCTURE



FY 90 - 91 PROGRAM CHANGES

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PATHFINDER

EXPLORATION TECHNOLOGY

SURFACE EXPLORATION

- Surface Power
- Planetary Rover
- Sample Acquisition, Analysis & Preservation
- Autonomous Lander
- Photonics

SURFACE OPERATIONS

- Space Nuclear Power
- Surface Solar Power
- Planetary Rover
- In Situ Resource Utilization
- Surface Habitats & Construction

IN-SPACE OPERATIONS

- Space Nuclear Power (SP-100)
- Autonomous Rendezvous & Docking
- In-Space Assembly & Construction
- Cryogenic Fluid Depot
- Resource Processing Pilot.
- Optical Communications



REVISED WORK BREAKDOWN STRUCTURE

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- SPACE R&T BASE
- IN-SPACE TECH. EXPER. PROG.



- SPACE R&T BASE

- CSTI PROGRAM
 - SCIENCE
 - TRANSPORTATION
 - OPERATIONS



- CIVIL SPACE TECHNOLOGY PROGRAM
 - SPACE SCIENCE TECHNOLOGY
 - TRANSPORTATION TECHNOLOGY
 - OPERATIONS TECHNOLOGY
 - SPACE EXPLORATION TECHNOLOGY
 - SPACE PLATFORMS TECHNOLOGY

- EXPLORATION TECHNOLOGY
 - SPACE TRANSPORTATION
 - IN-SPACE OPERATIONS
 - SURFACE OPERATIONS
 - HUMAN SUPPORT
 - LUNAR & MARS SCIENCE
 - NUCLEAR PROPULSION
- SPACE AUTOMATION & TELEROBOTICS

LBF 40257

REVISED WORK BREAKDOWN STRUCTURE

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- **SPACE R&T BASE**
 - Aerothermodynamics
 - Space Energy Conversion
 - Propulsion
 - Materials & Structures
 - Space Flight
 - Systems Analysis
 - University Space Research
 - Information and Controls
 - Human Support
- **IN-SPACE TECH. EXPER. PROG.**
- **CSTI PROGRAM**
 - **SCIENCE**
 - Science Sensor
 - High Rate/Capacity Data Systems
 - Precision Segmented Reflectors
 - **TRANSPORTATION**
 - Earth to Orbit
 - **OPERATIONS**
 - Telerobotics
 - Artificial Intelligence
 - High Capacity Power
 - Controls/Structures Interaction
- **EXPLORATION TECHNOLOGY**
 - **SPACE TRANSPORTATION**
 - Aerobraking
 - Space Based Engines
 - Autonomous Landing
 - Autonomous Rendezvous & Docking
 - **IN-SPACE OPERATIONS**
 - Cryogenic Fluid Systems
 - In-Space Assembly and Construction
 - **SURFACE OPERATIONS**
 - Space Nuclear Power
 - In-Situ Resource Utilization
 - **HUMAN SUPPORT**
 - Regenerative Life Support
 - Radiation Protection
 - Extravehicular Activities Systems (Surface)
 - Exploration Human Factors
 - **LUNAR & MARS SCIENCE**
 - Sample Acquisition, Analysis & Preservation
 - Planetary Probes & Penetrators
 - **NUCLEAR PROPULSION**
 - Nuclear Thermal Propulsion
 - **INNOVATIVE TECHNOLOGY**
 - Exploration Technology Analysis
- **SPACE AUTOMATION & TELEROBOTICS**
- **AEROASSIST FLIGHT EXPERIMENT**
- **SPACE R&T BASE**
 - Discipline Research
 - Aerothermodynamics
 - Space Energy Conversion
 - Propulsion
 - Materials & Structures
 - Information and Controls
 - Human Support
 - Adv. Communications
 - University Programs
 - Space Flight R&T
 - Flight Experiment Studies
 - IN-STEP
 - Systems Analysis
- **CIVIL SPACE TECHNOLOGY PROGRAM**
 - **SPACE SCIENCE TECHNOLOGY**
 - Science Sensing
 - Observatory Systems
 - Science Information
 - In Situ Science
 - Technology Flight Expts.
 - **TRANSPORTATION TECHNOLOGY**
 - ETO Transportation
 - Space Transportation
 - Technology Flight Expts.
 - **OPERATIONS TECHNOLOGY**
 - Automation & Robotics
 - Infrastructure Operations
 - Info. & Communications
 - Technology Flight Expts.
 - **SPACE EXPLORATION TECHNOLOGY**
 - Surface Systems
 - Human Support
 - Technology Flight Expts.
 - **SPACE PLATFORMS TECHNOLOGY**
 - Earth-Orbiting Platforms
 - Space Stations
 - Deep-Space Platforms
 - Technology Flight Expts.

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Space Power Technology

SPACE ENERGY CONVERSION R&T

~~OADP~~

OBJECTIVE

Provide the technology to meet power system requirements for future space missions, including growth Space Station, Earth orbiting spacecraft, lunar and planetary bases, and solar system exploration

SPACE ENERGY CONVERSION R&T

~~OADP~~

POWER TECHNOLOGY

R&T BASE ELEMENTS

- PHOTOVOLTAIC ENERGY CONVERSION
- CHEMICAL ENERGY CONVERSION
- THERMAL ENERGY CONVERSION
- POWER MANAGEMENT
- THERMAL MANAGEMENT

"TECHNOLOGY PUSH"

FOCUSED TECHNOLOGY PROGRAMS

- SPACE NUCLEAR POWER
- HIGH CAPACITY POWER
- SURFACE POWER & THERMAL MANAGEMENT
- MOBILE SURFACE SYSTEMS (POWER)
- LASER POWER BEAMING
- EARTH ORBITING PLATFORMS POWER & THERMAL MANAGEMENT
- SPACECRAFT POWER & THERMAL MANAGEMENT

"MISSION PULL"

BASE R&T PROGRAM SPACE ENERGY CONVERSION R&T

OBJECTIVES

- **Programmatic**
Provide the technology base to meet power system requirements for future space missions, including growth Space Station, Earth orbiting spacecraft, lunar and planetary bases, and solar system exploration
- **Technical**
 ≥300 W/kg Planar Array Technology
 100 - 200 Wh/kg Batteries
 ≥20% System Efficiency (Thermal-to Electric)
 >0.6 W/cm³ and >20 W/kg PMAD
 1 - 4 kg/m² Radiator Specific Mass

RESOURCES (\$M)

	CURRENT	3X	STRATEGIC
FY91	12.5	12.5	12.5
FY92	12.8	12.8	12.8
FY93	13.3	15.8	17.7
FY94	13.8	20.1	21.5
FY95	14.6	23.4	25.8
FY96	15.3	25.6	29.7
FY97	16.0	28.6	33.9

SCHEDULE

- 1992 12-panel APSA
Complete critical technology experiments for liquid sheet radiator (LSR)
- 1993 5-Ah Li-TiS₂ Engineering Model Demo
Solar Dynamic Heat Receiver Tech Demo
Prototype Smart Pole (PMAD)
- 1994 Demonstrate thin 20% InP Cell
Deliver Bipolar Flight Battery
15% Efficient, 3000-Hour AMTEC
- 1995 Complete 100 Wh/kg Nickel Hydrogen Battery
- 1996 Demo 600 K PMAD Test Bed
- 1997 Complete integrated thermal and electrical test of power electronics orbital replacement unit
- 1998 Demonstrate 2nd generation APSA (>200 W/kg)
- 1999 Ground test 330 W/m², 1 kW Concentrator Array

PARTICIPANTS

- **Lewis Research Center**
Responsibility includes advanced solar cells, nickel hydrogen & sodium sulfur batteries; dynamic conversion systems; fault-tolerant/high-temperature PMAD; thermal management
- **Jet Propulsion Laboratory**
Responsibility includes advanced arrays, lithium & advanced batteries; AMTEC; advanced thermoelectrics; power integrated circuits
- **Langley Research Center**
Space-based laser power technology
- **Goddard Space Flight Center**
Thermal management for space experiments

FOCUSED TECHNOLOGY PROGRAM SPACE ENERGY CONVERSION R&T

OBJECTIVES

- **Programmatic**
Provide the focused technology to meet power system requirements for lunar and planetary bases, planetary rovers, penetrators, Earth-orbiting spacecraft, and deep-space missions
- **Technical**
 ≥100 kW space nuclear reactor (7 years full power)
 1300 K Stirling (35% eff) and Thermoelectric (Z=1.0)
 1000 W-h/kg RFC with 20,000 h operational life
 PV (30% eff) and Thermoelectric (14% eff) for rovers
 >300 W/kg PV array (rad hard/LILT resistant)

RESOURCES (\$M)

	Current	3X	Strategic
FY-91	24	24	24
FY-92	30.6	30.6	30.6
FY-93	29.5	55.6	61.7
FY-94	29.6	100.5	127.1
FY-95	24.8	131.1	172.7
FY-96	25	140.5	202.3
FY-97	26.1	161	151.5

SCHEDULE

- 1993 Thermoelectric Multicouple, Z = .85
Stirling, 1050 K, 25 kW/cylinder, 25% efficient
- 1994 SP-100 NAT fuel pins fabricated/stored
600 K radiator demonstration
- 1995 Restart SP-100 Nuclear Assembly Test (NAT) Site
Mfg specs for Z = 1.0 Thermoelectric
Complete Phase I Development (Laser Beaming)
- 1996 Complete SP-100 T/E Converter /TEM pump tests
Stirling, 1050 K, 25 kW/cylinder (35% eff.)
Demonstrate 300 W/kg planar/100 W/kg InP conc.
- 1997 Ground demo of 2-kW solar dynamic system
Complete 5000 h on fuel cell stack
Complete Phase II Development (Laser Beaming)
- 1999 Stirling, 1300 K, 25 kW/cylinder (35% eff.)
- 2001 Complete SP-100 flight-like IAT (lunar outpost)

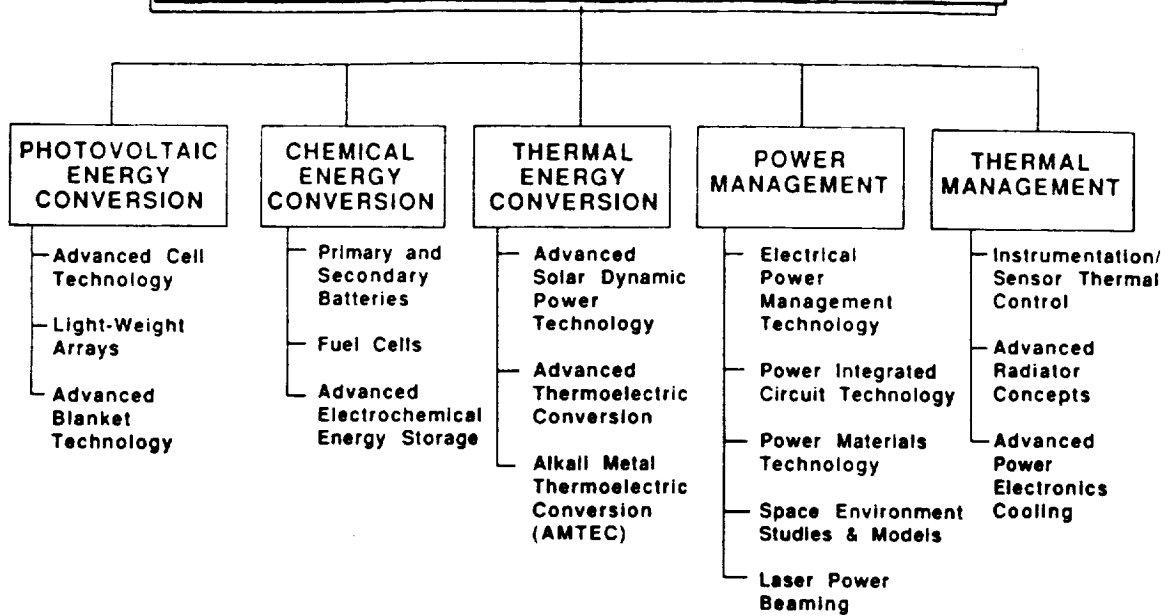
PARTICIPANTS

- **Lewis Research Center**
SP-100 space subsystems; lead for high capacity power, surface power; mobile systems power; power systems technology for platforms and rovers; FEL power beaming
- **Jet Propulsion Laboratory**
Lead for SP-100 GES; power system technology for platforms and rovers; FEL power beaming
- **Langley Research Center**
Laser power beaming
- **Goddard Space Flight Center**
Thermal management
- **Johnson Space Center**
Supporting technology for surface and mobile power
- **Marshall Space Flight Center**
Support on FEL power beaming

SPACE ENERGY CONVERSION R&T

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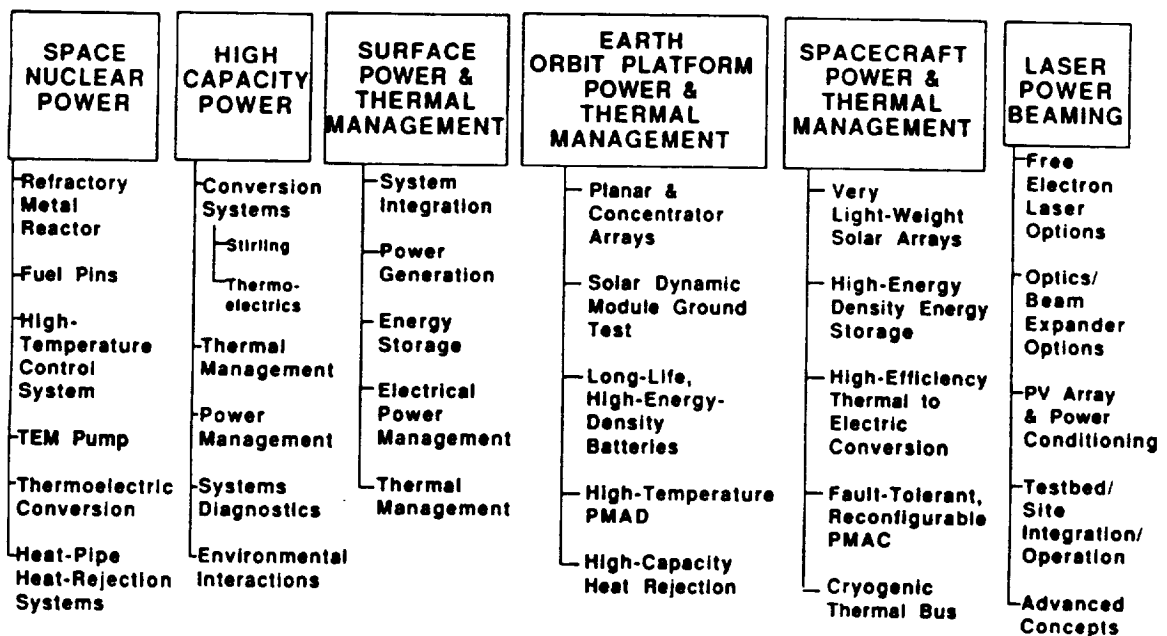
Base R&T Work Breakdown Structure



SPACE ENERGY CONVERSION R&T

~~ORAT~~

Focused Technology Work Breakdown Structure



SPACE ENERGY CONVERSION R&T

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Focused Technology Work Breakdown Structure

(Continued)

MOBILE SURFACE SYSTEMS (POWER)

- System Integration
- Photovoltaic Power Generation
- Energy Storage
- Power Management & Distribution
- Dynamic Isotope Power System (DIPS)
Ancillary Technology
- Thermal-to-Electric Generators
- Tribology

SPACE ENERGY CONVERSION R&T

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ROLES & PARTICIPANTS

POWER TECHNOLOGY

R&T BASE ELEMENTS

Photovoltaic Energy Conversion

LeRC (advanced cells/blankets)
JPL (Hgh-weight arrays)

Chemical Energy Conversion

LeRC (adv. batteries/fuel cells)
JPL (adv. batteries)

Thermal Energy Conversion

LeRC (adv. solar dynamic)
JPL (thermoelectrics/AMTEC)

Power Management

LeRC (PMAD/Materials/Environment)
JPL (PICs technology)
LeRC (power beaming)

Thermal Management

GSFC (sensor thermal control)
LeRC (adv. radiators/electronics cooling)

FOCUSED TECHNOLOGY PROGRAMS

Space nuclear power

JPL (project management)
LeRC (space subsystems)
DOE/SDIO/GE/LANL/HEDL/etc.

High capacity power

LeRC (project lead/Stirling)
JPL (thermoelectrics)

Surface power & thermal mgmt

LeRC (lead/PV/Storage/EPM/TM)
JPL (PV/Storage/TM) GSFC (TM)
JSC (Storage/TM) LANL (Storage)

Mobile Surface Systems

LeRC (lead)
JPL (P: .../Battery/TE/PMAD)
JSC (Fu... vorH. tests)

Laser Power Beaming

MSFC (FEL Test Site/Optics)
JPL (Optics/PV)
LeRC (PV)

Earth Orbit Platform Pwr & Thermal Mgmt

LeRC (PV/Batteries/
H-Temp TM/PMAD)
JPL (PV/Li batt/PMAD)
GSFC (Le-Temp TM)

Spacecraft Power & Thermal Mgmt

JPL (PV/PICs
Mission/TE/AMTEC)
LeRC (PMAC/DIPS/
PV/H-Temp Rad/
Reactor Analyses)
GSFC (Le-Temp TM)

- Heat Pipe Performance
- Solar Array Module Plasma Interaction Experiment (SAMPIE)
- Thermal Energy Storage
- Sodium-Sulfur Battery

Integrated Technology Plan Process

FY'93 ITP IMPLEMENTATION PLAN

● FOR NEAR-TERM NEEDS

IN '93-'97 BY 1993 THRU 1997:
 COMPLETE THE ONGOING PROGRAM;
 IMPLEMENT KEY SELECTED NEW TASKS
 DELIVER SELECTED HIGH-LEVERAGE
 SUBSYSTEM CAPABILITIES

● FOR END-OF-DECADE NEEDS

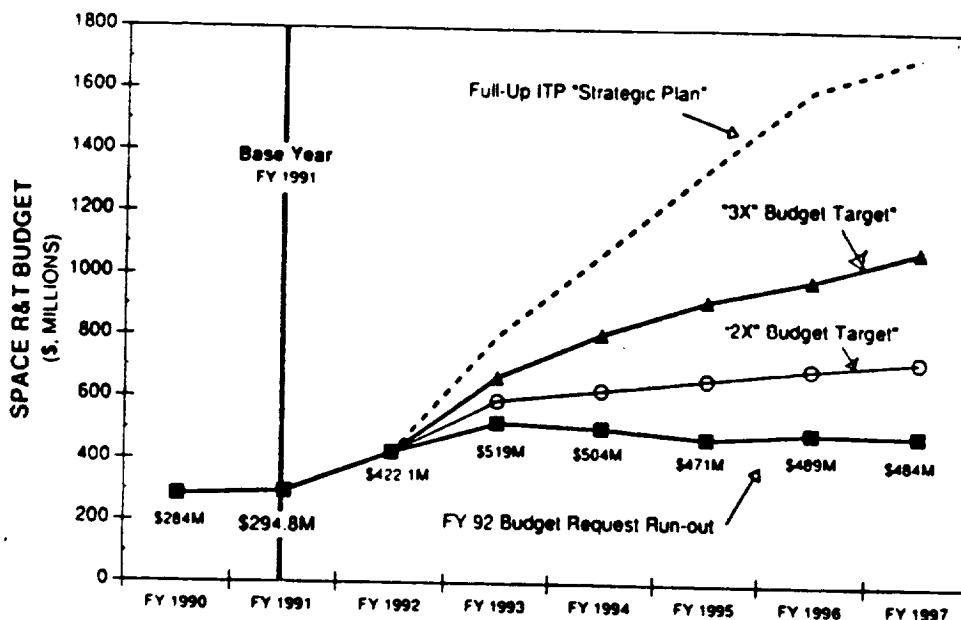
IN '93-'97 BEGIN BY 1998 THRU 2003:
 HIGH PRIORITY R&T; DELIVER MAJOR NEW SYSTEM CAPABILITIES
 BEGIN TO PUT CRITICAL CONDUCT MAJOR DEMONSTRATIONS/FLIGHT EXPERIMENTS
 R&T TESTBEDS & BEGIN SIGNIFICANT USE OF SSF FOR R&T
 FACILITIES IN PLACE LEVERAGE NASP DEMONSTRATIONS

● FOR LONG-TERM NEEDS

IN '93-'97 BEGIN BY 2004 THRU 2011
 SELECTED, LONG-TERM DELIVER MAJOR NEW SYSTEM CAPABILITIES
 R&T EFFORTS BEGIN USE OF LUNAR OUTPOST FOR R&T
 ACHIEVE MARS TECHNOLOGY READINESS

LBF40290a
 (JCM 7682a)

INTEGRATED TECHNOLOGY PL. FOR THE CIVIL SPACE PROGRAM SPACE R&T BUDGET IMPLICATIONS



FLIGHT PROGRAMS FORECAST

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● 5-YEAR FORECAST INCLUDES

'93 THRU '97: COMPLETION OF INITIAL SSF
LIMITED SOME SHUTTLE IMPROVEMENTS
NEW STARTS INITIAL EOS & EOSDIS
SELECTED SPACE SCIENCE STARTS
NLS DEVELOPMENT
INITIAL SEI ARCHITECTURE SELECTION
EVOLVING GEO COMMERCIAL COMMSATS
MINOR UPGRADES OF COMMERCIAL ELVS

● 10-YEAR FORECAST INCLUDES

'98 THRU '03: SSF EVOLUTION/INFRASTRUCTURE
MULTIPLE FINAL SHUTTLE ENHANCEMENTS
NEW STARTS ADVANCED LEO EOS PLATFORMS/FULL EOSDIS
TO BE LAUNCHED MULTIPLE SPACE SCIENCE STARTS
IN 2003 THRU 2010 NLS OPERATIONS/EVOLUTION
EVOLVING LAUNCH/OPERATIONS FACILITIES
INITIAL SEI LUNAR OUTPOST START
DSN EVOLUTION (KA-BAND COMMUNICATIONS)
NEW GEO COMMERCIAL COMMSATS
NEW COMMERCIAL ELVS

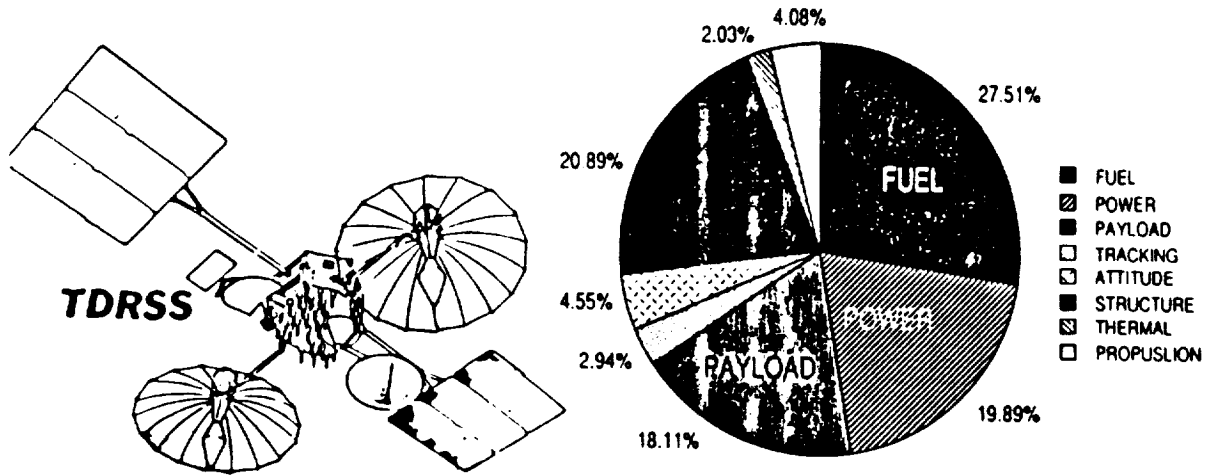
● 20-YEAR FORECAST INCLUDES

'04 THRU '11 SSF-MARS EVOLUTION
MULTIPLE BEGINNING OF AMLS/PLS DEVELOPMENT
OPTIONS FOR NEW MULTIPLE SPACE SCIENCE STARTS
STARTS TO BE DSN EVOLUTION (OPTICAL COMM)
LAUNCHED IN INITIAL MARS HLLV DEVELOPMENT
2009 THRU 2020 EVOLVING LUNAR SYSTEMS
MARS SEI ARCHITECTURE CHOSEN
LARGE GEO COMMSATS
NEW COMMERCIAL ELVS

LSF40305a
(JCM 7602)

***Space Power
Background***

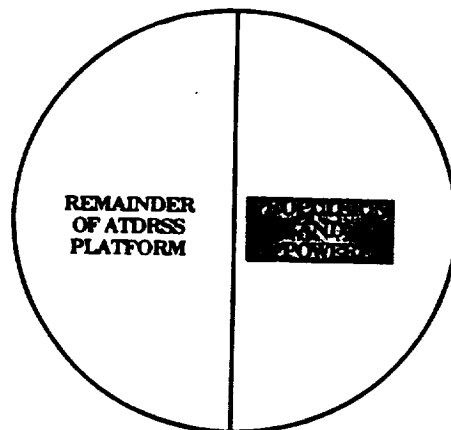
TRACKING AND DATA RELAY SATELLITE SYSTEM WET MASS



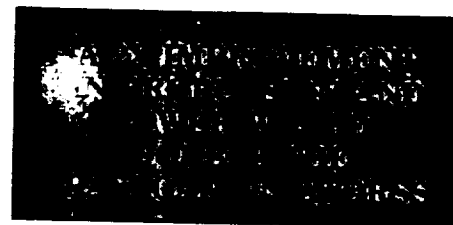
TOTAL MASS = 2123 kg

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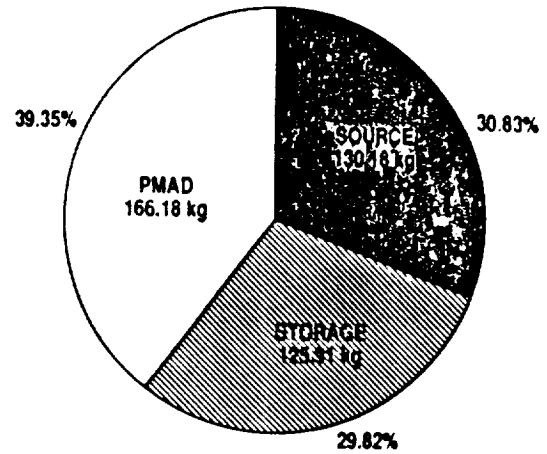
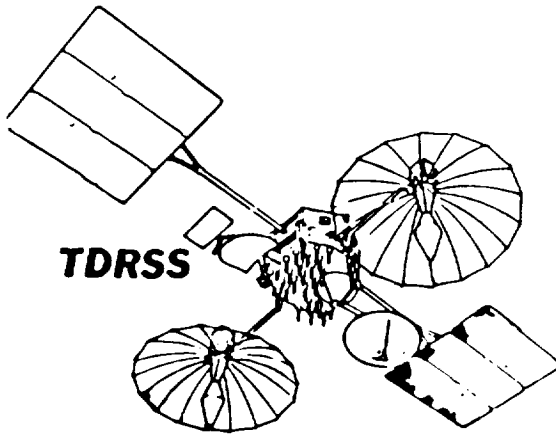
IMPROVEMENTS IN PROPULSION AND POWER CAN
SIGNIFICANTLY IMPROVE ATRDRSS



PROPULSION AND
POWER COMPRISE
ABOUT ONE-HALF
OF THE TOTAL MASS
OF ATRDRSS



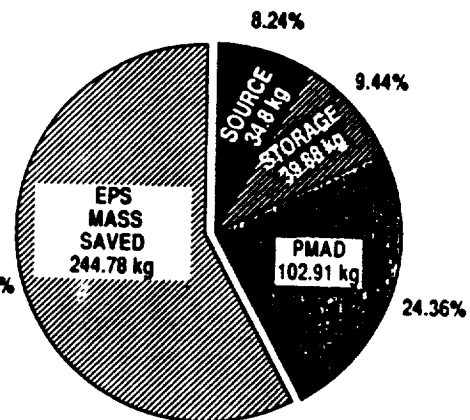
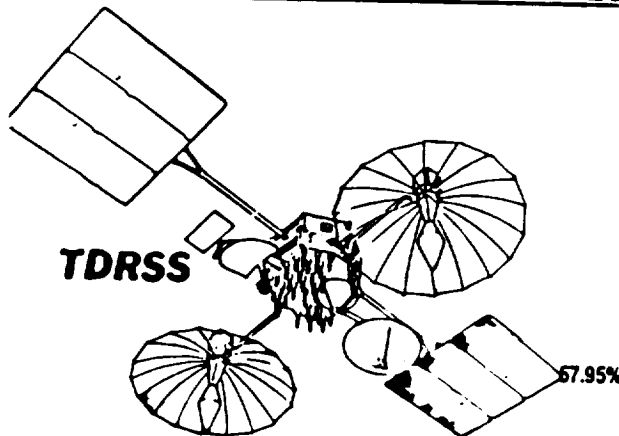
ELECTRICAL SUBSYSTEM MASSES



TOTAL EPS MASS = 422kg

BK91 001 11

ELECTRICAL POWER SYSTEM MASSES
WITH ADVANCED TECHNOLOGIES



ADVANCED POWER SYSTEM TECHNOLOGIES CAN SAVE
245 kg IN THE ELECTRICAL POWER SYSTEM

BK91 001 17

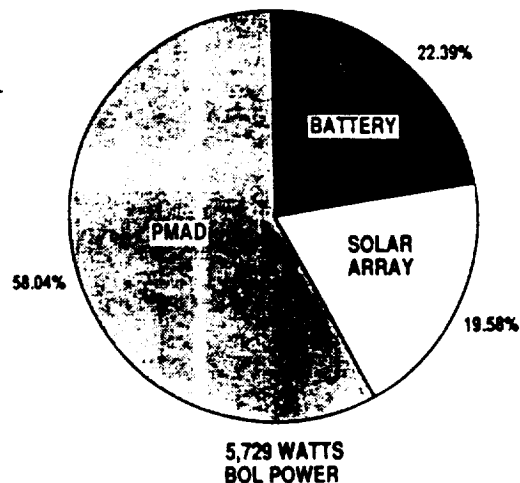
- NEW TECHNOLOGY ALLOWS 138% MORE POWER FOR THE SAME MASS
- FOR 422.3 kg, NEW TECHNOLOGY GIVES 5729 WATTS

SOLAR ARRAY MASS 82.67 kg

BATTERY MASS 94.53 kg

PMAD MASS 245.08 kg
422.28 kg

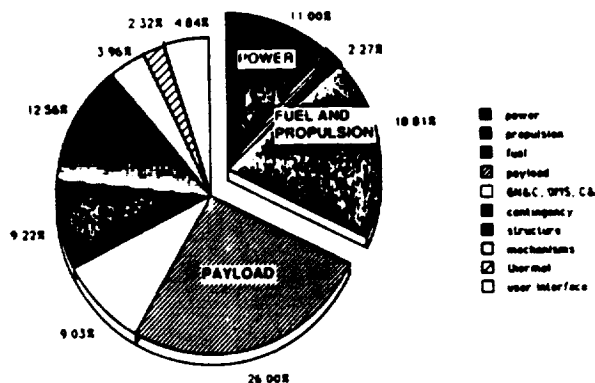
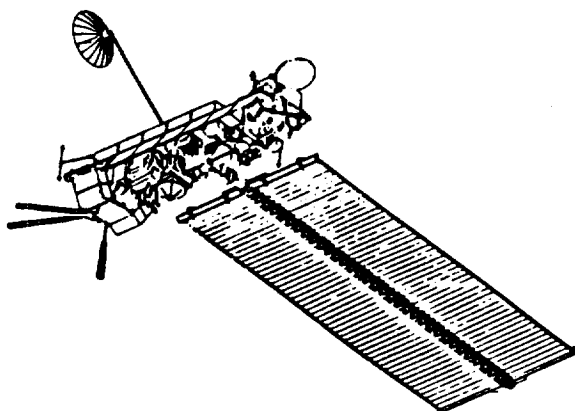
- ADDITIONAL 3319 WATTS OF POWER AVAILABLE WITH NEW TECHNOLOGY FOR THE SAME MASS



BK 91 01-1-pm

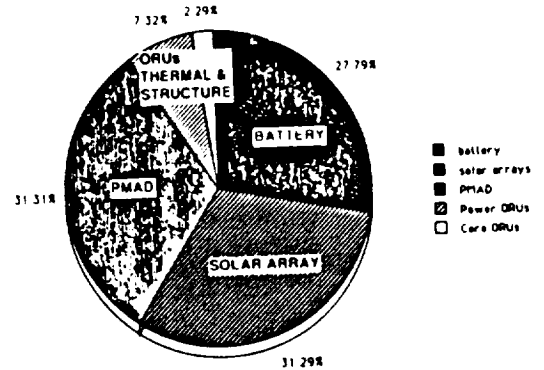
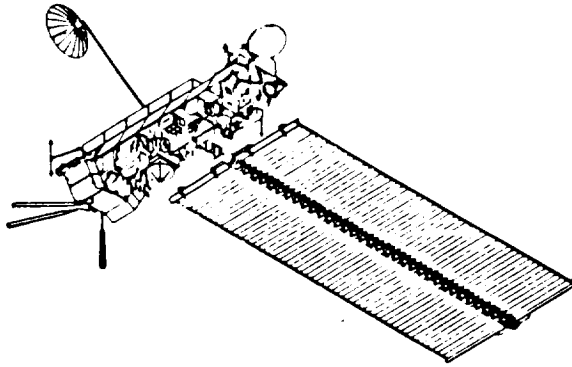
NASA Earth Observing System OAET

POLAR ORBITING PLATFORM WET MASS



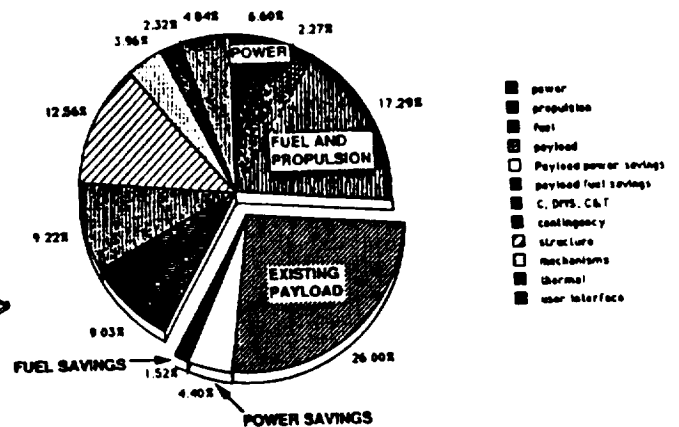
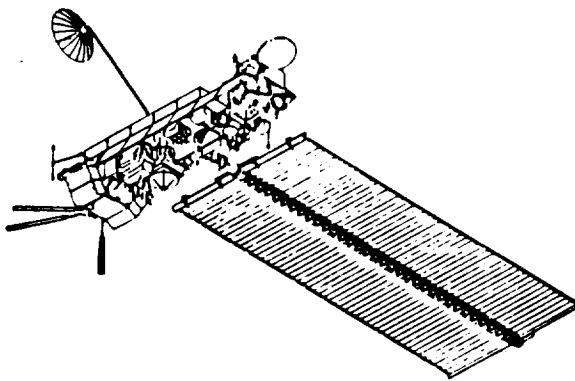
TOTAL WEIGHT IS 29715 lbs (13507 kg)

ELECTRICAL POWER SYSTEM WEIGHTS



TOTAL EPS WEIGHT IS 3264.8 lbs (1484 kg)

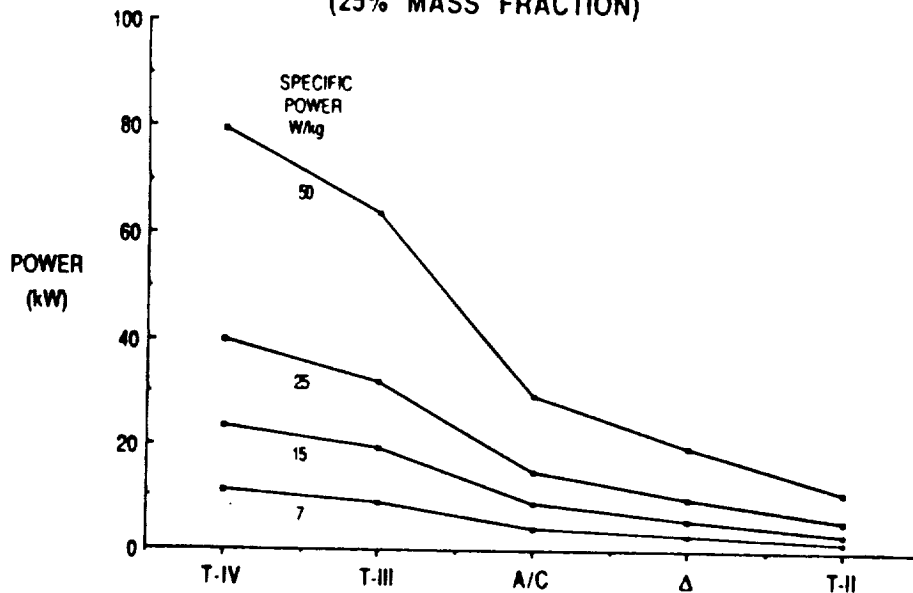
POLAR PLATFORM WEIGHT WITH ADVANCED TECHNOLOGIES



NEW TECHNOLOGIES ALLOW ~32% OF MASS TO BE PAYLOAD

IMPACT OF POWER SYSTEM SPECIFIC MASS ON GEO ORBIT POWER

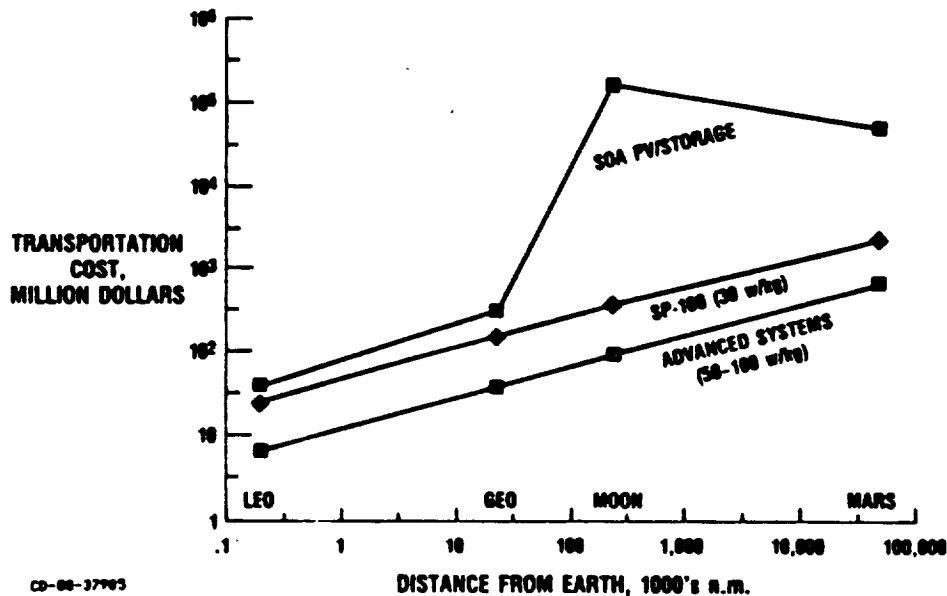
(25% MASS FRACTION)



KAF89.005.7

MSA
C-80-13155

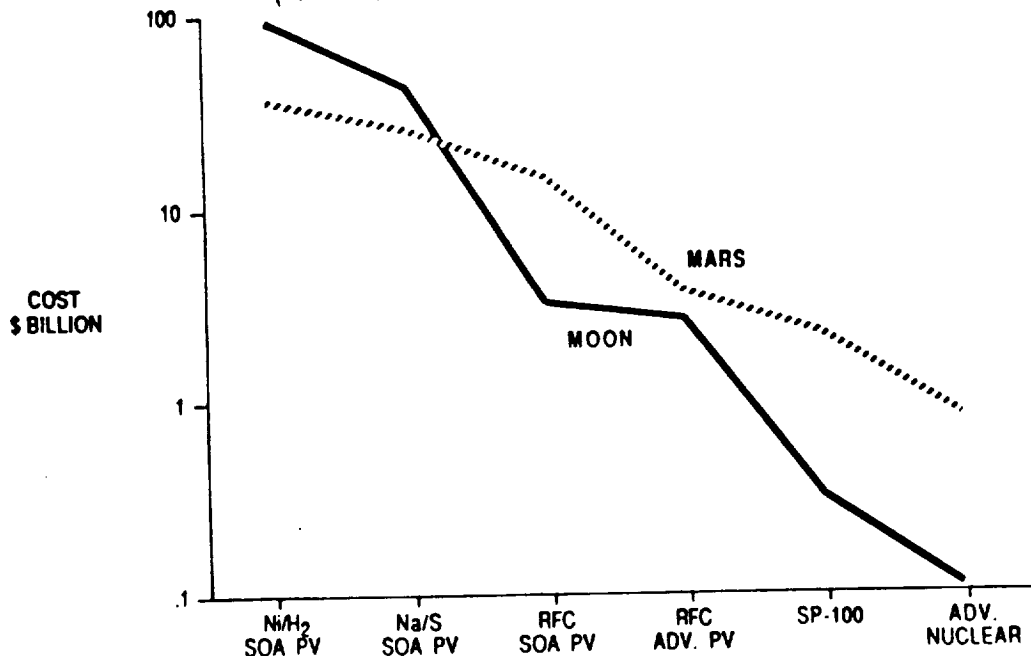
COST OF DELIVERING 100 kWe OF USABLE POWER



CD-88-37995

IMPACT OF POWER TECHNOLOGY ADVANCES ON TRANSPORTATION COSTS

(100 kWe, 1988 U.S. TRANSPORTATION COSTS)



SPACE ENERGY CONVERSION R&T

GAEL

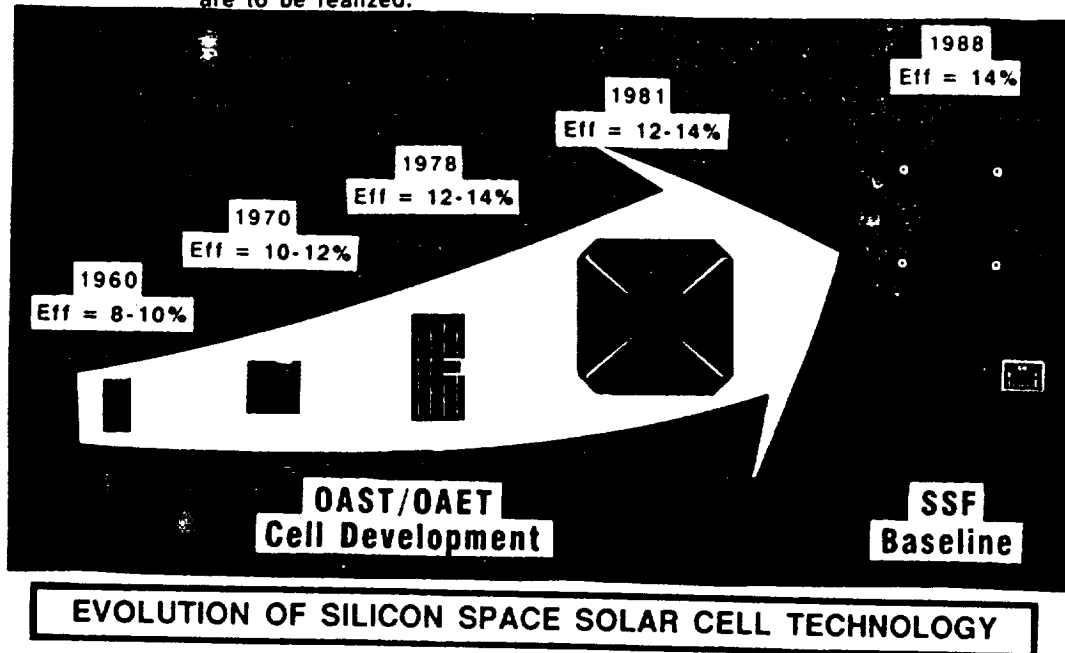
TECHNOLOGY SUPPORT

The Space Energy Conversion R&T Program Supports a Broad Range of Planned and Future NASA/DoD/Commercial Mission Power Requirements, Including

- Earth Observing Systems
- Space Station
- Communications Satellites
- Advanced Tracking and Data Relay Satellite System
- Lunar/Planetary Surface Power
- Planetary Spacecraft
- Electric Propulsion
- Missions to Comets and Asteroids
- Surface Explorers/Rovers
- Penetrators
- Launch and Orbital Transfer Vehicles

SPACE POWER TECHNOLOGY EVOLUTION

Space power technology evolution is and has been a long-term, steady improvement. There will be near-term spinoffs (as in the battery electrolyte for Hubble Space Telescope) as the technology evolves; however, there must be a long-term commitment to supporting the technology if the full benefits are to be realized.



Technology Needs

SPACE ENERGY CONVERSION R&T

~~OASD~~

TECHNOLOGY NEEDS

- OSSA

- HIGHEST PRIORITY

- 50 - 100 kWe Ion Propulsion (NEP) [Far-Term Need]

- SECOND HIGHEST PRIORITY

- Solar Array/Cells [Near-Term Need]
 - Radiation Hardened Parts/Detectors [Near-Term Need]
 - Long-Life/High-Energy Density Batteries [Near-Term Need]

- THIRD HIGHEST PRIORITY

- Mini RTG [Near-Term Need]
 - Thermal Control System [Mid-Term Need]

- OSF

- HIGHEST PRIORITY

- Advanced Heat Rejection Devices (Heat Pumps/Heat Pipes)
 - High-Efficiency Space Power Systems (PV Concentrator Cells/Solar Dynamic Systems)
 - Electromechanical Control Systems/Electrical Actuation
(advanced, integrated electric power systems with surge/demand capability)

SPACE ENERGY CONVERSION R&T

~~OASD~~

TECHNOLOGY NEEDS

(Continued)

- MFPE/SEI

- HIGHEST PRIORITY

- Surface Power (Category 2)
 - Electric Propulsion (Category 3)

Space Power Reviews and Studies

SPACE ENERGY CONVERSION R&T

~~OASD~~

**Summary of the 1990 Annual Review by the
Space Systems & Technology Advisory Committee
Aerospace Research & Technology Subcommittee**

ESSENTIAL

- **Maintain Vigorous Base R&T Program**
 - Source of New Ideas and Techniques
 - Training Ground for Next Generation Space Technologists
 - Impacts "World Technology Position"
 - High Probability for Commercial Spin-Off
 - Archival Value
- **Develop Long-Range Defendable Strategies**
 - Cooperative Programs Wherever Possible
 - Emphasize Commercial Potential Where Obvious
- **Promote/Force User Acceptance**
 - Space Qualification
 - Tech Transfer Mechanism

SPACE ENERGY CONVERSION R&T

~~CAST~~

Summary of the 1990 Annual Review by the Space Systems & Technology Advisory Committee Aerospace Research & Technology Subcommittee

HIGH PRIORITY

- **Space Nuclear Power**
 - Long Lead Time Technology
 - SEI Essential
 - Cooperative Agreements
- **Light Weight, Efficient Photovoltaics**
 - Growth Space Station
 - First Stages SEI
 - Commercial Spin Off
- **Efficient Energy Dense Storage Technology**
 - Regenerative Fuel Cells
 - Batteries
 - Thermal Storage
 - Significant Commercial Potential

SPACE ENERGY CONVERSION R&T

~~CAST~~

Summary of the 1990 Annual Review by the Space Systems & Technology Advisory Committee Aerospace Research & Technology Subcommittee

HIGH PRIORITY

(Continued)

- **Efficient Energy/Power Dense Power Management
and Conditioning**
 - Major Contributions to Spacecraft Weight and Volume
 - Significant Commercial Potential
 - Major Uncertainty in Scale Up

SPACE ENERGY CONVERSION R&T

~~OAEI~~

**Summary of the 1990 Annual Review by the
Space Systems & Technology Advisory Committee
Aerospace Research & Technology Subcommittee**

LOWER PRIORITY

- **Power Beaming**
 - No Strong Panel Advocate
 - Comments Ranged From Terminate to Keep Alive
- **Solar Dynamic Power**
 - User Should Develop (Space Station)
- **AMTEC (Alkali Metal Thermoelectric Conversion)**
 - Severe Materials Problem
 - Advanced Thermoelectrics/Thermionics Are Competitive
 - No Strong Panel Advocate

SPACE ENERGY CONVERSION R&T

~~OAEI~~

**Report of the Committee on Advanced Space Technology
Aeronautics and Space Engineering Board
National Research Council
(1987)**

SUMMARY RECOMMENDATIONS ON SPACE POWER

Space Power Supplies of the Future Should Include Photovoltaic, Solar Dynamic, and Nuclear Sources. Only Reactor-Generated Power Can Meet Anticipated High-Power Requirements, and NASA should Increase Its Involvement in the SP-100 Program, an Interagency Nuclear Space Power (SP) Research and Demonstration Program Designed to Achieve 100 kW of Space-Based Power.

SPACE ENERGY CONVERSION R&T

~~OASD~~

Report of the Committee on Advanced Space Technology Aeronautics and Space Engineering Board National Research Council (1987)

SPECIFIC RECOMMENDATIONS ON SPACE POWER

It is Recommended that NASA Continue to Strengthen Its Solar Power Technology and Stirling Engine Development Programs. It Should Build an Integrated Approach to Improving the Spacecraft Bus for a Wide Range of Mission Needs. This Also Should Include Meeting Lunar and Planetary Rover Requirements. NASA Should Expand the Scope and Magnitude of Its Nuclear Power Development Program. Specifically, NASA Should Become a Stronger Resource Contributor to the Total SP-100 Program, Expanding Its Effort, Now Limited to Conversion System Technologies. It Should, in Fact, Become a Full Partner in SP-100, Applying More of Its Resources to the Mainstream of the Program.

SPACE ENERGY CONVERSION R&T

~~OASD~~

Report of the Committee on Advanced Space Technology Aeronautics and Space Engineering Board National Research Council

SPECIFIC RECOMMENDATIONS ON SPACE POWER

(Continued)

Further, NASA Should Review Its Most Stressing Missions by Defining Requirements and Evaluating Power System Options Against the Specific Requirements. Optimal Combinations of Power Sources Should be Defined and R&D Programs Initiated on a Time Frame Appropriate With Anticipated Mission Scenarios. For the Nuclear Reactor Power System Option in Particular, it is Important to Introduce it Neither Too Soon Nor Too Late in This Long-Term Scenario.

Much to be Preferred is an Orderly, Properly Paced, Goal-Oriented R&D Program. This Program Should be Coordinated and Made Complementary to all of the Existing Programs and Sponsors . . . In Short, a National Space Nuclear Power Program is Needed . . .

SPACE ENERGY CONVERSION R&T

~~CAET~~

**Report of the Committee on Advanced Space Technology
Aeronautics and Space Engineering Board
National Research Council
(1987)**

CONCLUSIONS AND OBSERVATIONS ON SPACE POWER

As Energy Requirements for Scientific, Military, and Commercial Missions Increase, There Will be a Need for Larger, More Utility-Like Energy Systems. Desirable Power Supplies Include Photovoltaic, Solar Dynamic, and Nuclear; However, Only Nuclear Reactor Generated Power Can Meet Very High Requirements. The Space Nuclear Power Program has a Start-Stop History. It is Recommended that NASA Increase Its Participation in the SP-100 Program to Ensure That Its Own Future Requirements for High Energy are Met. R&D on Photovoltaic, Solar Dynamic, Stirling Engine, and Other Power Conversion Development Should Continue.

SPACE ENERGY CONVERSION R&T

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**Report of the 90-Day Study on
Human Exploration of the Moon and Mars
1989**

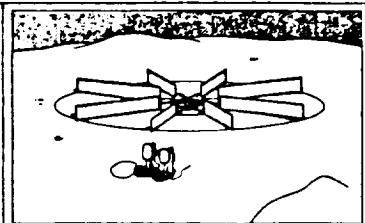
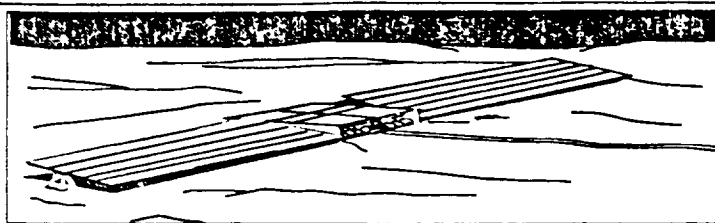
OTHER TECHNOLOGY NEEDS

- IN-SPACE OPERATIONS
- EARTH-TO-ORBIT TRANSPORTATION
- SPACE TRANSPORTATION
- SURFACE SYSTEMS
(includes surface nuclear power and surface solar power with chemical energy storage)
- HUMANS IN SPACE
- LUNAR AND MARS SCIENCE
- INFORMATION SYSTEMS AND AUTOMATION

Lunar Surface Power System Options

Strategy: Early Outpost Power Needs

Later Outpost Power Needs



• Power Generation

- Photovoltaic Arrays or Solar Dynamic Modules
 - Low-Moderate Mass/kW
 - Near Term Development
 - Can Be Located Near Outpost
 - Ease of Deployment
- Daytime Power Only
- Power Storage Required
- Moderate Spares
- Moderate Crew Support

• Power Storage

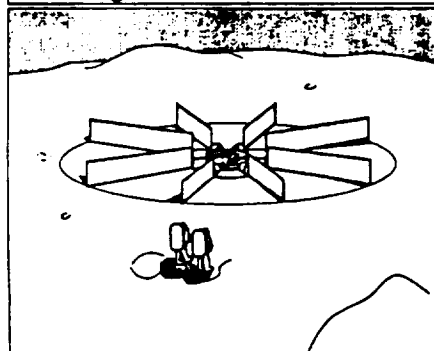
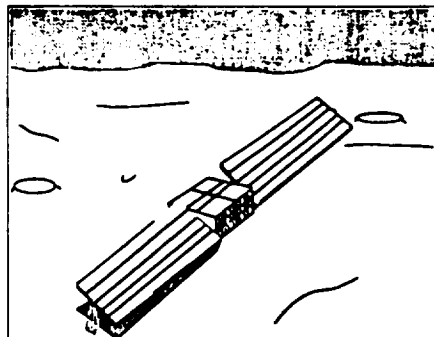
- Batteries
 - Near Term Development
 - High Initial Mass/kW
 - Short Lived Systems
- Regenerative Fuel Cells
 - Longer Term Development
 - Moderate Mass/kW
 - Short Lived Systems
 - High Spares/Resupply

• Nuclear Power

- Continuous Day/Night Power
- No Power Storage Required
- Low Initial Mass/kW
- Lowest Spares/Resupply
- Long Life Systems
- Minimum Crew Support
- Longer Term Development
- Must Be Remote to Outpost
- Radiation Shielding
- Political

Technical Study Group

SURFACE POWER SYSTEMS



PHOTOVOLTAIC ARRAY/ REGENERATIVE FUEL CELL

- Initial outpost power source
- 25/12.5 kW day/night capability
- State-of-the-art technology with large experience base
- Low power/mass ratio (1.5-3 W/kg)
- High resupply and sparing mass requirements (1t/year/unit)

SP-100 NUCLEAR REACTOR

- Dynamic engine power conversion
- 100 kW day/night capability
- High power/mass ratio (25-60 W/kg)
- Long life, high reliability system (7 year life)

Technical Study Group

SPACE ENERGY CONVERSION R&T

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Report of the Committee on Human Exploration of Space National Research Council (1990)

NUCLEAR ELECTRIC POWER

The Committee Believes that Nuclear Power Eventually Will be Essential for Lunar and Mars Bases. . .

At Present, the Only Active Technology Program Applicable to this Need is the SP-100 Thermoelectric Space Reactor, Which has Been Pursued Under a Tri-Agency Program for Several Years. SP-100 Was Initiated in the Absence of a Definite Mission Requirement as a General Purpose Space Reactor Power Source. This Program Should be Redefined in Light of the Requirements of the HEI and Committed to Development; Nuclear Thermionic Research Should Continue to be Pursued as Well.

SPACE ENERGY CONVERSION R&T

~~GAET~~

Report of the Committee on Human Exploration of Space National Research Council (1990)

NUCLEAR ELECTRIC POWER

(Continued)

Consideration Should be Given to Demonstration of the Nuclear Electric Power System as the Power Source for an Electric Propulsion System, Which May Have Application to Science Missions With Large Launch Velocity Requirements. (In Fact, a Number of Outer Planet Missions Have Been Suggested, Including a Jovian System Grand Tour, That Will Require Such Advanced Power Sources.) Here, as With the Nuclear Rocket, Considerations of Safety Must Be Incorporated into Research, Development, and Demonstrations and Factored into Assessments of Overall System Performance. The Nuclear Electric System Might be Demonstrated Within These Constraints by a Mission in Which the System is Launched to a High Orbit, Say 600 Miles, Before It is Operated. The Orbit Could Then be Raised by Nuclear-Electric Propulsion to Geosynchronous Orbit or Beyond.

Report of the Advisory Committee On the Future of the U. S. Space Program

Principal Recommendations Concerning Space Goals

- A science program, which enjoys highest priority within the the civil space program, and is maintained at or above the current fraction of the NASA budget
- A Mission to Planet Earth (MTPE) focusing on environmental measurements
- A Mission from Planet Earth (MFPE), with the long-term goal of human exploration of Mars, preceded by a modified Space Station which emphasizes life sciences, an exploration base on the Moon, and robotic precursors to Mars
- A significantly expanded technology development activity, closely coupled to space mission objectives, with particular attention devoted to engines
- A robust space transportation system

NASA

NATIONAL SPACE POLICY – GOALS

On November 2, 1989, the President approved a national space policy that updates and reaffirms U.S. goals and activities in space.

- Strengthen the security of the United States
- Obtain scientific, technological, and economic benefits
- Encourage private sector investment
- Promote international cooperative activities
- Maintain freedom of space for all activities
- Expand human presence and activity beyond Earth orbit into the solar system

Office of Aeronautics, Exploration and Technology

Barrow, Alaska 1989-10-26



SPACE ENERGY CONVERSION R&T

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REPORT OF THE SYNTHESIS GROUP RECOMMENDATIONS

SPECIFIC RECOMMENDATIONS ARE PROVIDED FOR THE EFFECTIVE
IMPLEMENTATION OF THE SPACE EXPLORATION INITIATIVE

RECOMMENDATION 7

**INITIATE A SPACE NUCLEAR POWER TECHNOLOGY
DEVELOPMENT PROGRAM BASED ON THE SPACE
EXPLORATION INITIATIVE REQUIREMENTS**

The Program Must Concentrate on Safe, Reliable Systems
to a Megawatt or Greater Level. These Nuclear Power
Systems Will Be Required for Use on the Moon Before
Use on the Mars Mission.

SPACE ENERGY CONVERSION R&T

CAET

REPORT OF THE SYNTHESIS GROUP POWER REQUIREMENTS

- TRANSPORTATION TO THE MOON REQUIRES POWER FOR ABOUT SEVEN DAYS FOR THE ROUND TRIP PLUS TIME IN LUNAR ORBIT
- TRANSPORTATION TO MARS INVOLVES TRIP TIMES ON THE ORDER OF A YEAR PLUS ORBITAL AND SURFACE OPERATIONS OF UP TO TWO YEARS
- SPACECRAFT WILL BE CONTINUOUSLY ROTATED IN CASES WHERE SOLAR FLUX IS VERY HIGH
- HABITAT POWER MUST HAVE A RELIABILITY >99.5%
- BASE POWER RELIABILITY CAN BE ABOUT 95%
- POWER UNITS SHOULD BE MADE OPERATIONAL
 - With a Minimum of Support Activities
 - Have Lifetimes Compatible with the Base
 - Be Serviceable
 - (If Nuclear) Be Refuelable and Disposable
- EVOLUTIONARY SYSTEMS DESIGNS ARE PREFERABLE TO SPECIFIC POINT DESIGNS WITHOUT GROWTH POTENTIAL

SPACE ENERGY CONVERSION R&T

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REPORT OF THE SYNTHESIS GROUP

FUNCTIONAL ELECTRICAL POWER REQUIREMENTS

Functions	Mars Power	Moon Power	Suggested Technology
Transportation			
Spacecraft			
Piloted	to 20 kw	to 30 kw	Fuel cells (Moon) Nuclear/photovoltaics (Mars)(1)
Cargo	5 kw	5 kw	Fuel cells (Moon) Photovoltaics (Mars)
Lander	20 kw	20 kw	Fuel cells (w/wo photovoltaics)
Electric propulsion	to 5 Mw	to 5 Mw	Nuclear
Surface Activities			
Day only	20 kw		Photovoltaics
Habitat/lab			
Initial Operational Capability	to 30 kw	to 50 kw	Photovoltaics or nuclear (1)
Next Operational Capability	50 kw	100 kw	Nuclear
Base Power			
Initial Operational Capability	to 100 kw	to 100 kw	Nuclear
Next Operational Capability	to 800 kw	to 1 Mw	Nuclear
Rovers			
Unloader/Construction	240 kw-hr	240 kw-hr	Fuel cells
Pressurized			
Initial Operational Capability (per trip)	1900 kw-hr	1900 kw-hr	Fuel cells (2)
Next Operational Capability (per trip)	4800 kw-hr	4800 kw-hr	Fuel cells (2)
Unpressurized	100 kw-hr	100 kw-hr	Fuel cells (2)

(1) Depends on final power level

(2) In situ methane and oxygen produced on Mars may substitute for fuel cells.

SPACE ENERGY CONVERSION R&T

~~OAEI~~

REPORT OF THE SYNTHESIS GROUP SUPPORTING TECHNOLOGIES

- HEAVY LIFT LAUNCH WITH A MINIMUM CAPABILITY OF 150 METRIC TONNES WITH DESIGNED GROWTH TO 250 METRIC TONNES
- NUCLEAR THERMAL PROPULSION
- NUCLEAR ELECTRIC SURFACE POWER TO MEGAWATT LEVELS
- EXTRAVEHICULAR ACTIVITY SUIT
- CRYOGENIC TRANSFER AND LONG TERM STORAGE
- AUTOMATED RENDEZVOUS AND DOCKING OF LARGE MASSES
- ZERO GRAVITY COUNTERMEASURES
- RADIATION EFFECTS AND SHIELDING
- TELEROBOTICS
- CLOSED LOOP LIFE SUPPORT SYSTEMS
- HUMAN FACTORS FOR LONG DURATION SPACE MISSIONS
- LIGHT-WEIGHT STRUCTURAL MATERIALS AND FABRICATION
- NUCLEAR ELECTRIC PROPULSION FOR FOLLOW-ON CARGO MISSIONS
- IN SITU RESOURCE EVALUATION AND PROCESSING

SPACE ENERGY CONVERSION R&T

~~OAEI~~

REPORT OF THE SYNTHESIS GROUP BASELINE DECISIONS FOR POWER

- FOR MARS, NUCLEAR POWER IS RECOMMENDED OVER PHOTOVOLTAICS DUE TO THE MASS SAVINGS. THE NUCLEAR UNITS WILL BE DEVELOPED TO MARS SPECIFICATIONS, AND THE MOON WILL BE USED TO VALIDATE THE DEPLOYMENT CONCEPT AND DEMONSTRATE SAFE AND RELIABLE OPERATION
 - Power Levels to a Megawatt for Base Power, Including Power for in situ Resource Processing, Refueling Surface Vehicles, and Emergency Habitat Power
 - Designed for Both the Moon and Mars Environments
 - Specific Power >100 W/kg at 1 MW
 - Deployed With a Minimum of Robotic or Human Operations
 - Lifetimes Must Be on the Order of 30 Years
- ADVANCED REGENERATIVE FUEL CELLS COULD PROVIDE POWER FOR LUNAR SPACECRAFT, LANDERS, AND SURFACE VEHICLES, WITH PERFORMANCE GREATER THAN 1 kW-h/kg
- NUCLEAR POWER UNITS (10 TO 100 kW) CAN PROVIDE POWER FOR MARS SPACECRAFT AND LUNAR AND MARS SURFACE HABITATS. THESE SYSTEMS SHOULD HAVE A SPECIFIC POWER >15 W/kg AT 25 kW, RELIABILITY >99.5%, PASSIVE CONVERSION AND NO SINGLE FAILURE POINTS
- ADVANCED SOLAR PHOTOVOLTAIC ARRAYS, WITH SPECIFIC POWERS >200 W/kg, CAN PROVIDE POWER FOR SPACECRAFT AND DAYTIME SURFACE OPERATIONS

SPACE ENERGY CONVERSION R&T

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REPORT OF THE SYNTHESIS GROUP RECOMMENDATIONS FOR DEVELOPMENT PROGRAMS

- THE CURRENT SP-100 AND THERMIONIC PROGRAMS SHOULD BE RESTRUCTURED TO MEET SPACE EXPLORATION INITIATIVE REQUIREMENTS
 - All Technology Options Should be Considered
 - Technology Down-Selections Should be Based on Demonstrated Performance, Safety and Reliability
 - The Benefits Provided by Nuclear Power Systems are Extremely High and are Key Enablers for Many Initiative Activities; However, New Efforts to Develop Space Applications of Nuclear Power Should be Structured to Take Advantage of Lessons Learned From the SP-100 Program
- ADVANCED REGENERATIVE FUEL CELLS CAN BE DEVELOPED BY THE YEAR 2000. THE COST IS LOW WITH WIDE APPLICATION TO CRITICAL SURFACE SYSTEMS SUCH AS LANDERS AND ROVERS
- SOLAR PHOTOVOLTAIC ARRAYS COULD PLAY A WIDE RANGE OF ROLES IN THE INITIATIVE. INCREASING THE EFFICIENCY AND DECREASING THE WEIGHT OF SOLAR ARRAYS WILL CONTINUE TO PAY HIGH DIVIDENDS FOR BOTH SPACE- AND EARTH-BASED APPLICATIONS
- POWER BEAMING FOR SURFACE-TO-SURFACE POWER DISTRIBUTION MAY GREATLY REDUCE THE MASS OF ROVERS AND OTHER MOBILE SURFACE SYSTEMS, ASSUMING LINE OF SITE CONSTRAINTS CAN BE MET. IF NUCLEAR ELECTRIC PROPULSION IS DEVELOPED FOR USE IN THE LUNAR OR MARS CARGO VEHICLE, THE ORBITING TRANSFER VEHICLE MAY BE A CONVENIENT POWER SOURCE FOR SURFACE OPERATIONS (NOTED NEED TO CONSIDER COSTS)

***Space Power
Technology
Development***

SPACE ENERGY CONVERSION R&T

O&T

TECHNOLOGY DEVELOPMENT CHALLENGES/DRIVERS

- DEVELOP POWER SYSTEMS FOR AND EXTEND THEIR LIFE IN FUNCTIONAL ENVIRONMENTS (LEO, GEO, MOON, PLANETARY)
- INCREASE POWER DENSITY OF POWER SYSTEM
- REDUCE POWER SYSTEM MASS
- INCREASE POWER SYSTEM RELIABILITY
- ENABLE POWER SYSTEM OPERATION AT HIGHER TEMPERATURES

AUGMENTATION

- ACCELERATE DEVELOPMENT OF POWER SYSTEM TECHNOLOGIES
- AUGMENT R&T AREAS THAT ARE MINIMALLY FUNDED
- INITIATE MISSION-FOCUSED AND ADVANCED TECHNOLOGIES
- TRANSFER MATURING TECHNOLOGIES TO FOCUSED THRUSTS AND USERS

SPACE ENERGY CONVERSION R&T

O&T

TECHNOLOGY BENEFITS

- REDUCED LAUNCH WEIGHT
- INCREASED POWER FOR SAME MASS
- INCREASED LIFETIME
- INCREASED RELIABILITY
- REDUCED COSTS
- EXTENDED RANGE OF POWER SYSTEM CAPABILITIES
- REDUCED VOLUME

SPACE ENERGY CONVERSION R&T

~~ORNL~~

TECHNOLOGY DEVELOPMENT APPROACH

- DEVELOP AND EVALUATE HIGH-EFFICIENCY, RADIATION-HARD SOLAR CELLS AND LIGHT-WEIGHT ARRAY SYSTEM COMPONENTS
- DEVELOP ADVANCED HIGH SPECIFIC ENERGY, HIGH ENERGY DENSITY, LONG CYCLE LIFE ENERGY STORAGE SYSTEMS
- DEVELOP IMPROVED THERMAL-TO-ELECTRIC CONVERSION SYSTEMS
(Advanced thermoelectric materials, AMTEC, solar dynamic, Stirling)
- DEVELOP LIGHT-WEIGHT, SMART, HIGH-TEMPERATURE, COMPACT POWER MANAGEMENT AND CONTROL (PMAC)
- DEVELOP INNOVATIVE, LOW-MASS THERMAL TRANSPORT AND RADIATOR CONCEPTS
- DEVELOP SP-100 SPACE NUCLEAR REACTOR POWER SYSTEM

SPACE ENERGY CONVERSION R&T

~~ORNL~~

TECHNOLOGY DEVELOPMENT APPROACH

(Continued)

- DEVELOP LASER POWER BEAMING CAPABILITY
- DEVELOP IMPROVED POWER SYSTEM MATERIALS
- DEVELOP ENVIRONMENTAL INTERACTIONS MODELS AND DESIGN GUIDELINES FOR FUTURE SPACE POWER SYSTEMS

SPACE ENERGY CONVERSION R&T

~~ORBIT~~

RECENT ACCOMPLISHMENTS

- SUCCESSFUL COMPLETION OF GROUND TESTING OF 130 W/kg ADVANCED PHOTOVOLTAIC SOLAR ARRAY (APSA)
- BOEING APPLICATION OF NASA-SPONSORED MINI-DOME FRESNEL LENS AND PRISMATIC CELL COVER TO ACHIEVE 31% AMO EFFICIENCY
- SUCCESSFUL COMPLETION OF 40,000 LEO CYCLES AT 80% DEPTH OF DISCHARGE (DOD) IN BOILER PLATE NICKEL-HYDROGEN CELLS
- SUCCESSFUL COMPLETION OF >10,000 CYCLES IN BIPOLAR NICKEL-HYDROGEN
- SUCCESSFUL ACHIEVEMENT OF 700 CYCLES AT 50% DOD IN 1-A-h LiTiS₂ CELLS

SPACE ENERGY CONVERSION R&T

~~ORBIT~~

RECENT ACCOMPLISHMENTS

(Continued)

- SUCCESSFUL REPRODUCTION OF HI-
SILICON-GERMANIUM-GALLIUM-PHOS
MATERIAL
- DEMONSTRATED FEASIBILITY OF FABRICATION
TECHNIQUES FOR SOLAR DYNAMIC CONCENTRATOR
ALUMINUM PANELS
- DEMONSTRATED STABILITY OF LIQUID SHEET RADIATOR
AT 1-G (VERIFIED ANALYTICAL PREDICTIONS)
- SUCCESSFULLY TESTED SILICON-CARBIDE MOSFET
TO 500 C
- DEVELOPED MONTE CARLO MODEL FOR ATOMIC OXYGEN
EROSION
- DEMONSTRATED 7X INCREASE IN ATOMIC OXYGEN DURABILITY
WITH CVD-DEPOSITED SiO₂ ON CARBON/CARBON COMPOSITE
RADIATOR SURFACES

SPACE ENERGY CONVERSION R&T

SPACE POWER SYSTEMS

TECHNOLOGY NEEDS

HIGH POWER, HIGH EFFICIENCY,
LOW-MASS ELECTRICAL POWER SYSTEMS AND
THERMAL MANAGEMENT SYSTEMS FOR SPACECRAFT AND PLANETARY BASES

CURRENT PROGRAM S-O-A

COMMERCIAL SOLAR ARRAYS AT ~20 W/kg (RIGID) TO ~66 W/kg (FLEXIBLE);
NASA/JPL LABORATORY DEMONSTRATION AT 130 W/kg; COMMERCIAL BATTERIES AT ~10 Wh/kg;
NASA TECHNOLOGY >20 Wh/kg; THERMOELECTRIC EFFICIENCY <7%; AND POWER MANAGEMENT
AND DISTRIBUTION (PMAD) AT <0.03 W/cm³ (AND <15 W/kg)

AUGMENTED PROGRAM

SOLAR ARRAYS AT 300 W/kg; BATTERIES AT 150 W-h/kg;
STATIC THERMAL-TO-ELECTRIC CONVERSION ≥10%; PMAD AT ≥0.6 W/cm³
(AND 20 W/kg) TO ACHIEVE FACTOR OF TWO REDUCTIONS IN MASS OF
ELECTRIC POWER SYSTEM ON SPACECRAFT

BASE RESEARCH AND TECHNOLOGY PROGRAM

SPACE ENERGY CONVERSION R&T

SUB-ELEMENT	STATE-OF-THE-ART	OBJECTIVE
PHOTOVOLTAICS	Comm: 20 W/kg (rigid) to 66 W/kg (flex.) Demo: 100 W/kg (rigid) to 130 W/kg (flex.) 240 W/m ²	> 300 W/kg (flex.) 1000 W/kg (blanket) >300 W/m ² (concentrator)
CHEMICAL ENERGY CONVERSION	Comm: 10 Wh/kg Demo: >20 Wh/kg	150 Wh/kg (75 % DOD)
THERMAL ENERGY CONVERSION	< 7 % efficiency	> 10 % efficiency
POWER MANAGEMENT	< 0.03 W/cm ³ <15 W/kg	> 0.6 W/cm ³ > 20 W/kg
THERMAL MANAGEMENT	10 kg/m ²	1-4 kg/m ²

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OF POOR QUALITY

BASE RESEARCH AND TECHNOLOGY PROGRAM
SPACE ENERGY CONVERSION R&T

SPACE POWER SYSTEMS

MISSION SPECIFIC

300 W/m² CONCENTRATORS, 300 W/kg SOLAR ARRAYS
100 W-hr/kg BATTERIES
600K POWER ELECTRONICS AND THERMAL CONTROL
HIGH FREQUENCY POWER
ATOMIC OXYGEN PROTECTIVE COATINGS/ARC PROOF SOLAR ARRAYS
ORBITAL AND PLANETARY SURFACE ENVIRONMENTAL DESIGN GUIDELINES

BREAKTHROUGH

LI/CO₂ FUEL CELLS
BEAMED POWER SYSTEMS
LUNAR REGOLITH STORAGE
1-2 kg/m² RADIATORS/ADVANCED HEAT PIPES
DIAMOND FILM POWER ELECTRONICS

CAPABILITY

PV PERFORMANCE VERIFICATION/FUNDAMENTALS
ELECTROCHEMICAL ADVANCED DIAGNOSTICS/MODELLING
SOLAR DYNAMIC DESIGN/ANALYSIS
HEAT PIPE CODE VALIDATION
SPACE ENVIRONMENTAL SIMULATION FACILITIES

RJS91-004.1

BASE RESEARCH AND TECHNOLOGY PROGRAM
SPACE ENERGY CONVERSION TECHNOLOGY

DAET

AUGMENTATION STRATEGY

- **HIGH-RISK, INNOVATIVE POWER TECHNOLOGIES THAT HAVE THE POTENTIAL OF HIGH PAYOFF FOR FUTURE MISSIONS**
 - DIAMOND FILM POWER ELECTRONICS
 - LI/CO₂ FUEL CELLS
- **MAINTAIN A BALANCE BETWEEN TECHNOLOGY ELEMENTS TO SUPPORT EVOLUTIONARY SPACECRAFT POWER SYSTEM NEEDS**
 - PHOTOVOLTAIC ENERGY CONVERSION
 - CHEMICAL/THERMAL ENERGY CONVERSION
 - POWER/THERMAL MANAGEMENT
- **MAINTAIN SPECIFIC ACTIVITIES TO ENHANCE NASA'S CAPABILITY TO RESPOND TO TECHNOLOGY NEEDS**
 - ADVANCED DIAGNOSTICS/MODELLING
 - SPACE ENVIRONMENTAL SIMULATION FACILITIES

FOCUSED TECHNOLOGY PROGRAMS
SPACE ENERGY CONVERSION R&T

~~OAEI~~

AUGMENTATION STRATEGY

- DEVELOP **HIGH-RISK, INNOVATIVE** POWER TECHNOLOGIES THAT HAVE THE POTENTIAL OF HIGH PAYOFF FOR THE SPACE EXPLORATION INITIATIVE (SEI) AND OTHER SPACE MISSIONS.

EXAMPLES: - SP-100 coupled with advanced conversion and radiators
- High specific energy regenerative fuel cells
- Laser power beaming

- BUILD ON BASE R&T PROGRAM TO **FOCUS** ON FUTURE SPACECRAFT POWER NEEDS

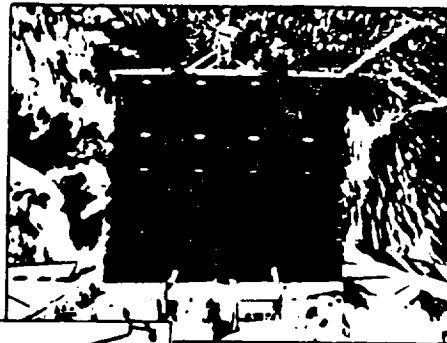
EXAMPLES: - Chemical/thermal energy conversion tie into high capacity power and surface power, etc.
- Power/thermal management tie into focused power programs



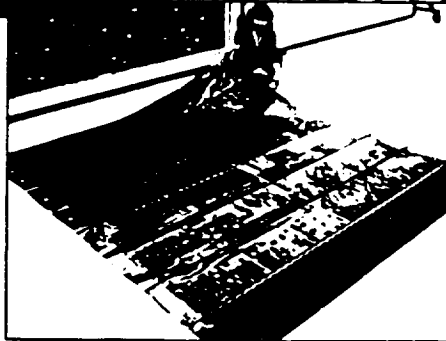
PROGRESS IN SOLAR ARRAY TECHNOLOGY



TDRS
30 W/kg



SAFE
66 W/kg



APSA
130 W/kg

RP00-388 (3)

SPACE ENERGY CONVERSION R&T

~~ORBIT~~

PHOTOVOLTAIC ENERGY CONVERSION

- OBJECTIVES

Provide the technology for photovoltaic arrays with improved conversion efficiency, reduced mass, reduced cost, and increased operating life for advanced space missions

- PARTICIPANTS

- Lewis Research Center
- Jet Propulsion Laboratory
- Industry/University Contracts

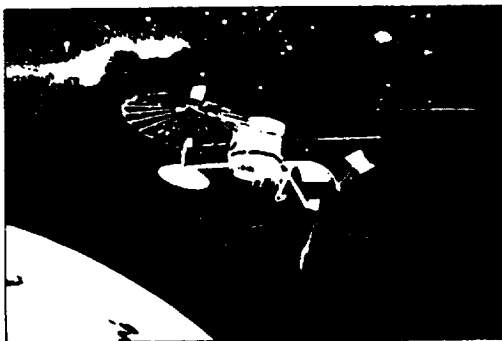
- AUGMENTATION

- Accelerate work on Advanced Photovoltaic Solar Array
- Development of thin 20% efficient InP solar cell (radiation hard)
- Accelerate development of thin-film flexible blanket
- Demonstrate high-temperature blanket
- Ground test 330 W/m² 1-kWe concentrator array

- PAYOFF

Lighter weight, longer lived arrays

PROGRESS IN ENERGY STORAGE



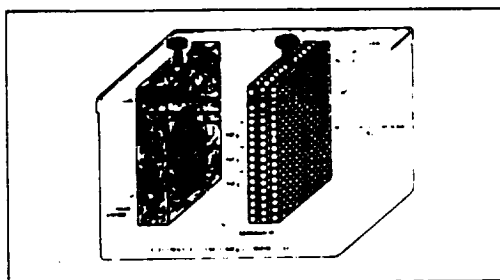
TDRS

Nickel Cadmium - 10 W-hr/kg



Space Station and Beyond

Nickel Hydrogen - 20+ W-hr/kg



Future Applications

Lithium Titanium Disulfide - 40+ W-hr/kg

SPACE ENERGY CONVERSION R&T

~~CAS~~

CHEMICAL ENERGY CONVERSION

- OBJECTIVES

Provide the technology base for advanced electrochemical energy conversion and storage systems required to support the low to high power needs and cycle life requirements for future space missions

- PARTICIPANTS

- Lewis Research Center
- Jet Propulsion Laboratory
- Industry/University Contracts

- AUGMENTATION

- Accelerate work on sodium sulfur batteries
- Expand/enhance work of fuel cell catalysts
- Develop and transfer lithium secondary battery technology
- Accelerate development of 150 W-h/kg cell
- Initiate electrochemical capacitor work

- PAYOFF

Lighter weight, longer lived batteries/More power for same mass

NASA
National Aeronautics and
Space Administration



SPACE ENERGY CONVERSION R&T

~~GAET~~

THERMAL ENERGY CONVERSION

- OBJECTIVES

- Develop the technology base to provide advanced high-efficiency, high-temperature, long-life solar dynamic Stirling/Brayton power system
- Develop new thermoelectric material with significantly higher figure of merit
- Investigate and demonstrate the feasibility of high-power, long-life alkali metal thermoelectric converter (AMTEC)

- PARTICIPANTS

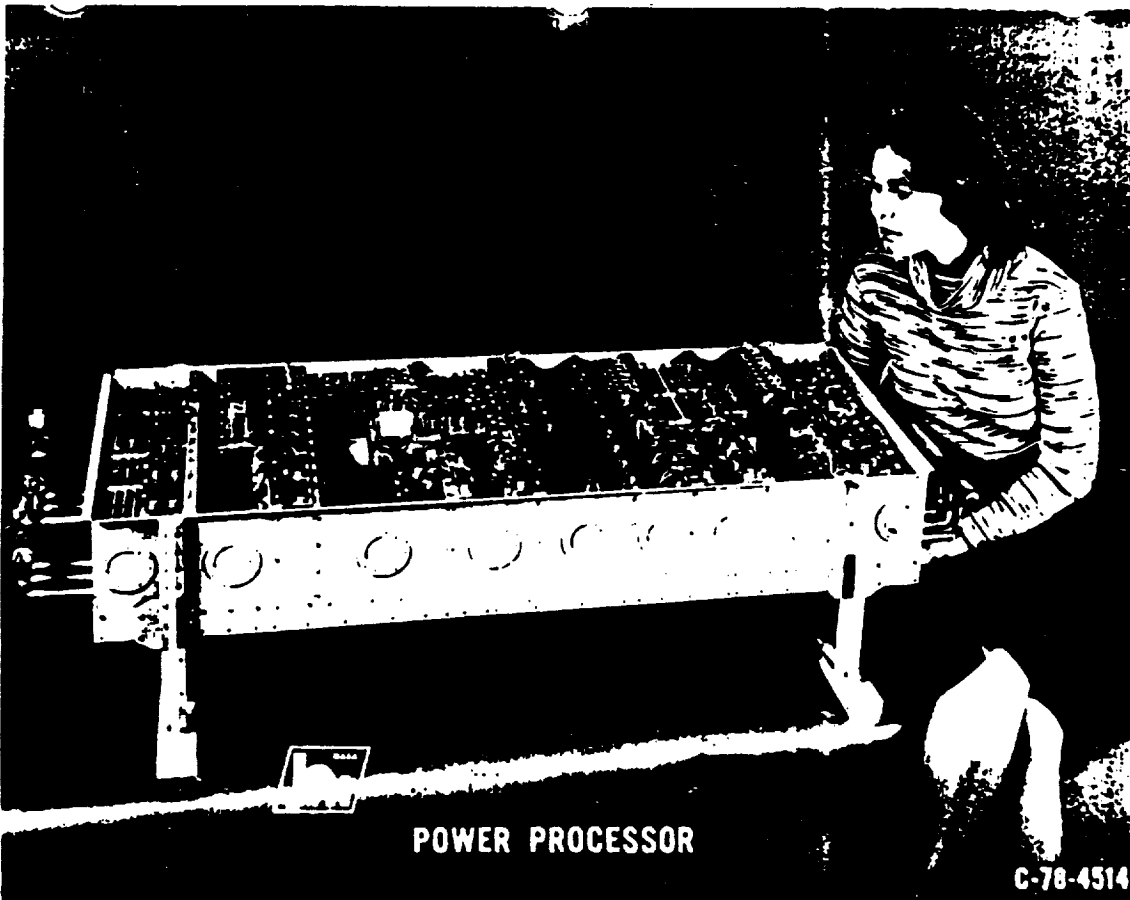
- Lewis Research Center
- Jet Propulsion Laboratory
- Industry/University Contracts

- AUGMENTATION

- Accelerate development of static conversion technologies
- Verify thermal energy storage technologies for lunar base application

- PAYOFF

- Reduction in radioisotope inventory
- Reduction in transported mass to Moon



SPACE ENERGY CONVERSION R&T

~~OAFT~~

POWER MANAGEMENT

- OBJECTIVES

- Develop the electrical power systems conditioning, control, and distribution technology for future space missions
- Development of the capability to model power systems (including environmental interactions)
- Development of advanced concepts (e.g., power beaming and advanced power management materials)

- PARTICIPANTS

- Lewis Research Center
- Jet Propulsion Laboratory
- Langley Research Center
- Industry/University Contracts

- AUGMENTATION

- Brings Power Management up to its level of importance
- Accelerates work on modular, high-temperature, smart PMAD

- PAYOFF

- Reliable, fault-tolerant power systems
- Reduced mass, reduced volume, reduced parts count

SPACE ENERGY CONVERSION R&T

~~OAFT~~

THERMAL MANAGEMENT

- OBJECTIVES

- Develop the technology base for versatile thermal management systems for next generation of space missions
- Provide advanced thermal management technology for both high and moderate temperatures, including technology for thermal control of instrument systems

- PARTICIPANTS

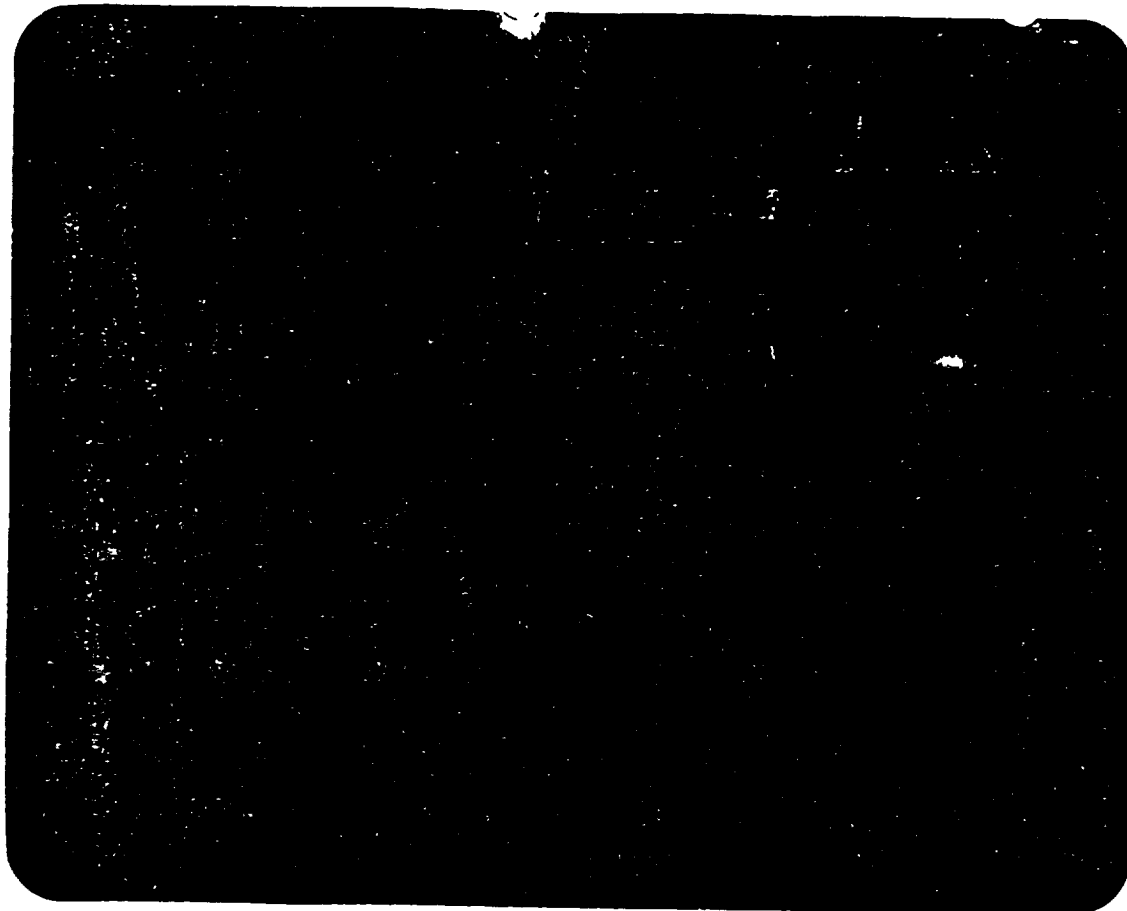
- Goddard Space Flight Center
- Lewis Research Center
- Industry/University Contracts

- AUGMENTATION

- Brings Thermal Management up to its level of importance
- Provides additional options for thermal management

- PAYOFF

- Reduction in radiator size and mass
- Major improvement ($\geq 50\%$) in sensor cooling



SPACE ENERGY CONVERSION R&T

~~ORAT~~

SPACE NUCLEAR POWER

- OBJECTIVES

Develop and validate the technologies for safe and reliable space nuclear reactor power systems to support lunar and Mars exploration missions

- PARTICIPANTS

- Lewis Research Center
- Jet Propulsion Laboratory
- DOE/SDIO/USAF
- Industry/University Contracts

- AUGMENTATION

Meets NASA's funding commitments under the MOU so that the SP-100 program can stay on schedule

- PAYOFF

A flexible power source that can span a range of power levels up to 1 MWe for space and surface bases with improved specific mass and lifetime

SPACE ENERGY CONVERSION R&T

~~CADP~~

HIGH CAPACITY POWER

- OBJECTIVES

Develop and demonstrate low-mass, reliable, long-lived power conversion technologies for space nuclear reactor power systems

- PARTICIPANTS

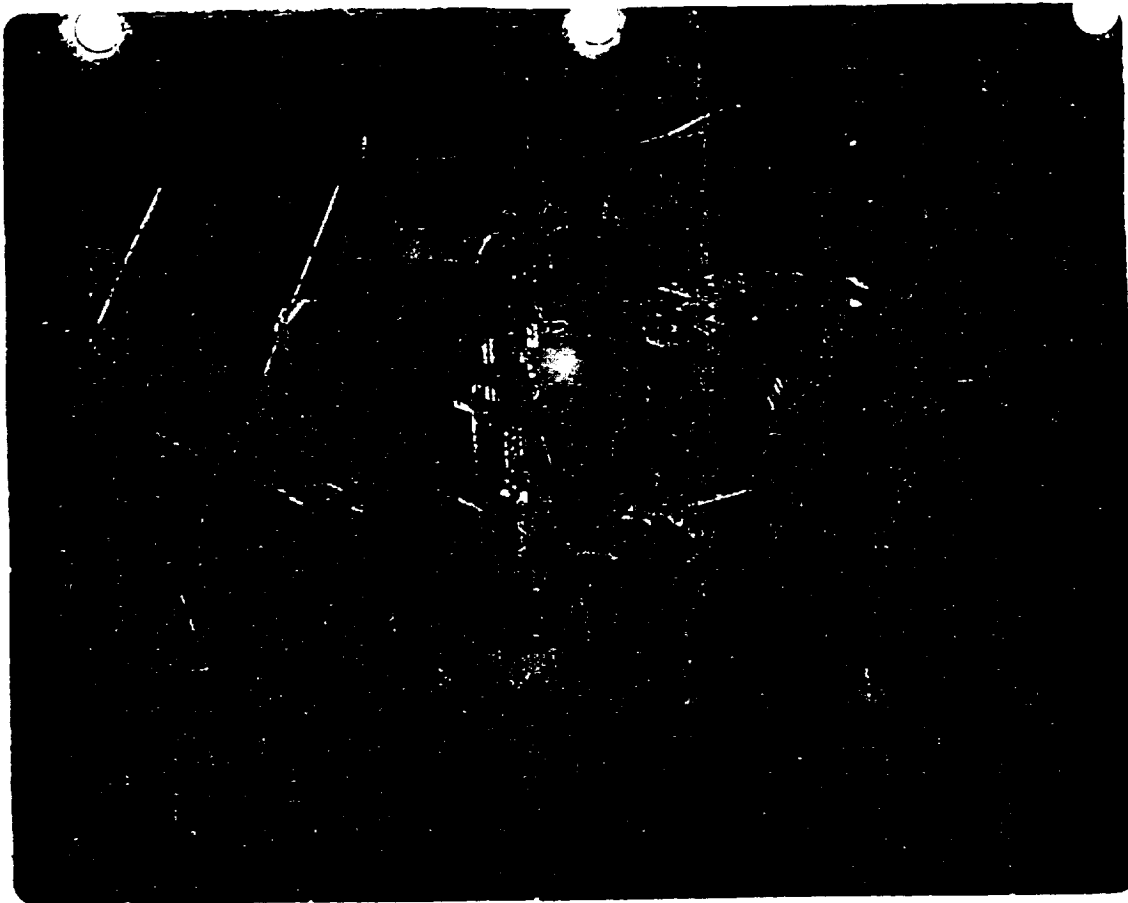
- Lewis Research Center
- Jet Propulsion Laboratory
- Industry/University Contracts

- AUGMENTATION

Allows development and demonstration of 1300 K Stirling conversion system (35% efficient) in time for early SEI use

- PAYOFF

Provides SP-100 with the conversion technology to scale up to 1 MWe



SPACE ENERGY CONVERSION R&T

CAST

SURFACE POWER & THERMAL MANAGEMENT

- **OBJECTIVES**

Develop solar-based power and low-grade heat thermal management technologies to support lunar and Mars surface system operations

- **PARTICIPANTS**

- Lewis Research Center
- Jet Propulsion Laboratory
- Johnson Space Center
- Goddard Space Flight Center
- Los Alamos National Laboratory
- Industry/University Contracts

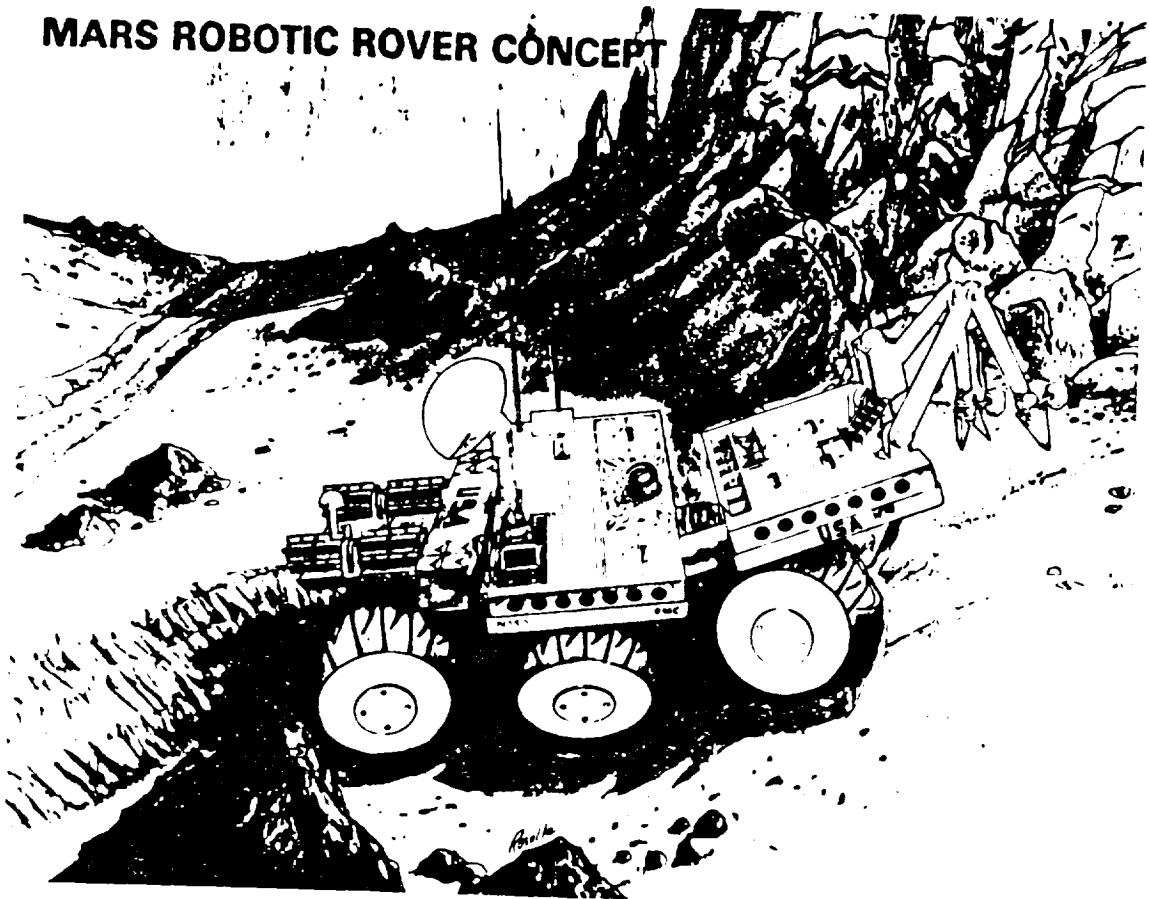
- **AUGMENTATION**

Allows funding for a solar-based surface power system that will be essential to the first exploration/outpost missions and for backup

- **PAYOFF**

Provides a light-weight, reliable, solar-based power system for lunar and Mars applications

MARS ROBOTIC ROVER CONCEPT



SPACE ENERGY CONVERSION R&T

~~ORAT~~

MOBILE SURFACE SYSTEMS (POWER)

- **OBJECTIVES**

Develop compact power technologies to a level of readiness sufficient to enable mobile and portable extraterrestrial surface power systems

- **PARTICIPANTS**

- Lewis Research Center
- Jet Propulsion Laboratory
- Johnson Space Center
- Industry/University Contracts

- **AUGMENTATION**

Reinstates mobile surface power systems program enabling work on system integration, power generation (PV and nuclear), energy storage, tribology, PMAD, small free-piston Stirling engine, convective heat exchangers for Martian surface mobile and/or portable dynamic isotope power systems

- **PAYOFF**

Provides mobile power system options that can span the range from <1 kWe to >20 kWe with varying power ratios and usages for a hostile, dusty environment.

MOBILE SURFACE SYSTEMS (POWER) SPACE ENERGY CONVERSION R&T

OBJECTIVES

• Programmatic

Develop compact power technologies to a level of readiness sufficient to enable mobile and portable extraterrestrial surface power systems

• Technical

Power Generation 14% efficient thermoelectric couple
30% efficient PV cell
Energy Storage >50 W-h/kg battery
>350 W-h/kg (Fuel cell @ 10 h)
PMAD 30% improvement in operating efficiency

SCHEDULE

- 1994 Recommend primary technology candidates with options
- 1996 Complete fab of bipolar Ni/H₂ battery
Mtg prototype multicouple @ Z = 0.85
- 1997 Establish preliminary design of fuel cell
Select battery technology
- 1998 Select PMAD's fractional horsepower optimized motor/controller
- 1999 Demonstrate combined Z = 1.4 (14% eff @ 1300 K)
Optimize efficiency of bottom cell of PV tandem cell
- 2001 Complete performance verification on modified test bed
Dem. sliding/rolling, dust seal and lube options

RESOURCES (\$M)

	<u>Current</u>	<u>3X</u>	<u>Strategic</u>
FY-91	3	3	3
FY-92	0	0	0
FY-93	0	0	0
FY-94	0	0	3
FY-95	0	0	3.2
FY-96	0	0	8
FY-97	0	0	10.4

PARTICIPANTS

- **Lewis Research Center**
Lead center in all technology elements
- **Jet Propulsion Laboratory**
Support in PV cell and array technology
Innovative PMAD technology
Support in battery technology
Thermoelectric technology
- **Johnson Space Center**
Supporting verification tests of fuel cells

SPACE ENERGY CONVERSION R&T

~~OAET~~

MOBILE SURFACE SYSTEMS (POWER)

• TECHNOLOGY NEEDS

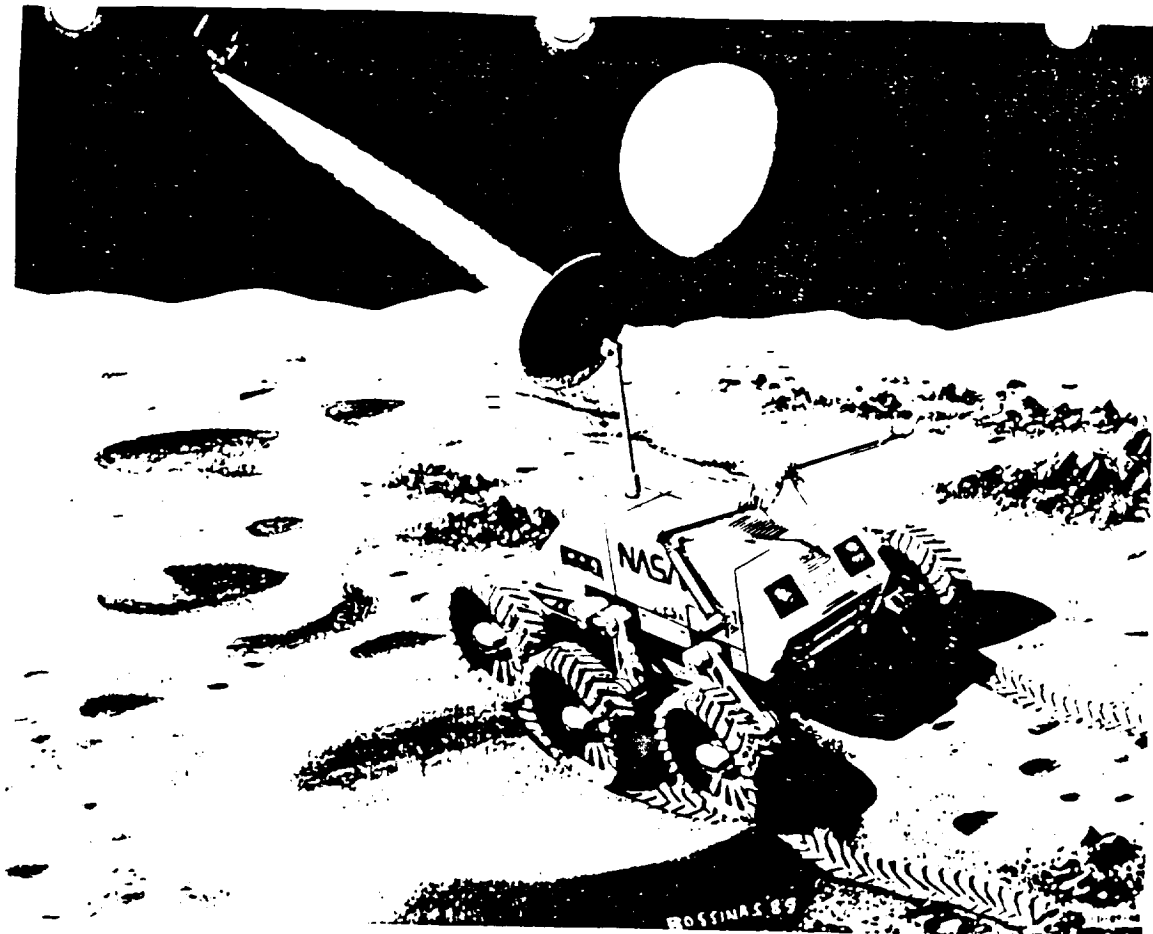
Rover and portable extraterrestrial surface systems have been shown to require power levels ranging from <1 kWe to >20 kWe with peak-to-average power ratios >10. Mission durations vary from intermittent to continuous use in a hostile, dusty environment.

• PROGRAMMATIC

Original program, Planetary Rover Project, will be terminated in FY 1992. The budget plan allows for restarting the program in FY 1994. The original power subelement of Planetary Rover was limited to improving the performance of thermoelectric materials.

• STRATEGIC PROGRAM

The resources under the Strategic budget would permit system studies, focused power generation and energy storage technology, tribology, and PMAD in the relevant environment and duty cycles.



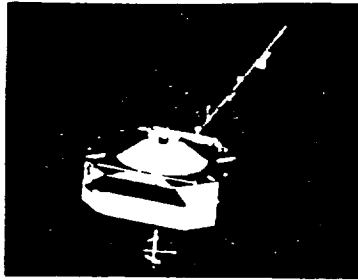
SPACE ENERGY CONVERSION R&T

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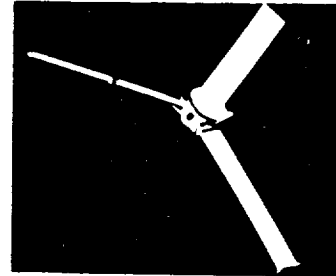
LASER POWER BEAMING

- **OBJECTIVES**
Develop and demonstrate the technologies and subsystems for laser power beaming from Earth to Moon
- **PARTICIPANTS**
 - Jet Propulsion Laboratory
 - Lewis Research Center
 - Marshall Space Flight Center
 - MIT Lincoln Lab/LLNL/Industry/University Contracts
- **AUGMENTATION**
Initiates a new thrust to develop the technologies (free electron laser/optics/PV/PMAD) to enable an advanced power supply systems
- **PAYOFF**
Provides a revolutionary way to power lunar surface bases and rovers with greatly reduced mass and launches.

**PLANETARY ORBITERS
(MERCURY ORBITER)**



**MISSIONS TO COMETS (COMET NUCLEUS
SAMPLE RETURN TAIL PROBE)**



MARS ROVER



**PENETRATORS
(GLOBAL NETWORK MISSION)**



SPACE ENERGY CONVERSION R&T

CASH

SPACECRAFT POWER AND THERMAL MANAGEMENT

- **OBJECTIVES**

Develop and demonstrate integrated spacecraft bus technologies for deep space applications

- **PARTICIPANTS**

- Jet Propulsion Laboratory
- Lewis Research Center
- Goddard Space Flight Center
- Industry/University Contracts

- **AUGMENTATION**

Initiates a new thrust to (1) demonstrate high power density solar array with deployment and LILT resistant; (2) develop advance static or dynamic conversion systems for radioisotope sources; define integration issues/advantages of reactor-powered science spacecraft; (3) develop energy storage for penetrators; (4) develop advanced PMAC and thermal management for deep space missions

- **PAYOFF**

Provides high specific power solar arrays and high efficiency converters with advanced PMAC and energy storage to reduce mass and/or increase power of deep space missions

SPACECRAFT POWER AND THERMAL MANAGEMENT SPACE ENERGY CONVERSION R&T

OBJECTIVES

- **Programmatic**
Develop and demonstrate integrated spacecraft bus technologies for deep space applications including both PV and nuclear power sources
- **Technical**
 - Assess advantages and issues of reactor power systems
 - Reduce PV array mass by 5X
 - Reduce radioisotope inventory by up to 4X
 - Provide autonomous reconfigurable power system with 2X mass reduction, 75% parts reduction
 - Reduce radiator mass and area by 2X
 - Develop advanced, integrated sensor cooling technology
 - Extend life (2 - 3X) and impact capability of primary batteries

SCHEDULE

- 1994 Select radioisotope power technology
Select advanced bus regulator (hybrid components)
- 1996 Demonstrate 300+ W/kg planar PV blanket
Design primary battery structure
- 1997 Demonstrate reactor integration, issues and potential advantages
Flight test advanced cryo heat pipes
Dem adv. radioisotope conversion module
Dem eng load power converter (hybrid comp)
- 1998 Dem light-weight radiator tech & primary batteries
Dem low noise instrument power converter using hybrid components
- 1999 Dem integrability of advanced power conversion module with radioisotope power source and 10-year life capability (modeling)

RESOURCES (\$M)

	<u>Current</u>	<u>3X</u>	<u>Strategic</u>
FY-91	0	0	0
FY-92	0	0	0
FY-93	0	0	2
FY-94	0	0	3.5
FY-95	0	0	6
FY-96	0	0	7.5
FY-97	0	0	9.1

PARTICIPANTS

- **Jet Propulsion Laboratory**
Light-weight planar PV array and power integrated circuits (PICs); mission impact assessments; static conversion systems for radioisotope power sources
- **Lewis Research Center**
Autonomous PMAC subsystems; dynamic conversion technologies for radioisotope power sources; nuclear reactor analyses; moderate and high temperature radiators; and thin film photovoltaics
- **Goddard Space Flight Center**
Low temperature thermal management subsystems

SPACE ENERGY CONVERSION R&T

OAET

SPACECRAFT POWER & THERMAL MANAGEMENT

• TECHNOLOGY NEEDS

Deep space missions will require reduced radioisotope mass (cost/availability issue) and/or improved performance from photovoltaic arrays (low light/low temperature issue). Inner solar system spacecraft will need high-temperature-resistant arrays. All require lower PMAD mass, battery mass, and radiator mass.

• PROGRAMMATIC

The ongoing R&T Base program is generically focused since resources do not permit covering all types of spacecraft. Currently there is no focused technology on assessing, developing, or demonstrating power technologies for deep space missions.

• STRATEGIC PROGRAM

The resources under the Strategic budget would focus on increased radioisotope-based system efficiency (reduces fuel requirements and cost). These resources would enable extending the range of photovoltaic capabilities (<1 AU to ~5 AU). In parallel, these resources would enable similar operational environment extensions for the other power system components.

SPACE ENERGY CONVERSION R&T

EAET

EARTH ORBIT PLATFORM POWER & THERMAL MANAGEMENT

- **OBJECTIVES**

Develop and demonstrate integrated power and thermal management technologies for near-Earth missions.

- **PARTICIPANTS**

- Lewis Research Center
- Jet Propulsion Laboratory
- Goddard Space Flight Center
- Industry/University Contracts

- **AUGMENTATION**

Initiates a new thrust to develop planar and concentrator arrays immune to the space environment with 100 W-h/kg battery systems, integrated, high-efficiency autonomous PMAC, and integrated thermal management for high-temperature electronics

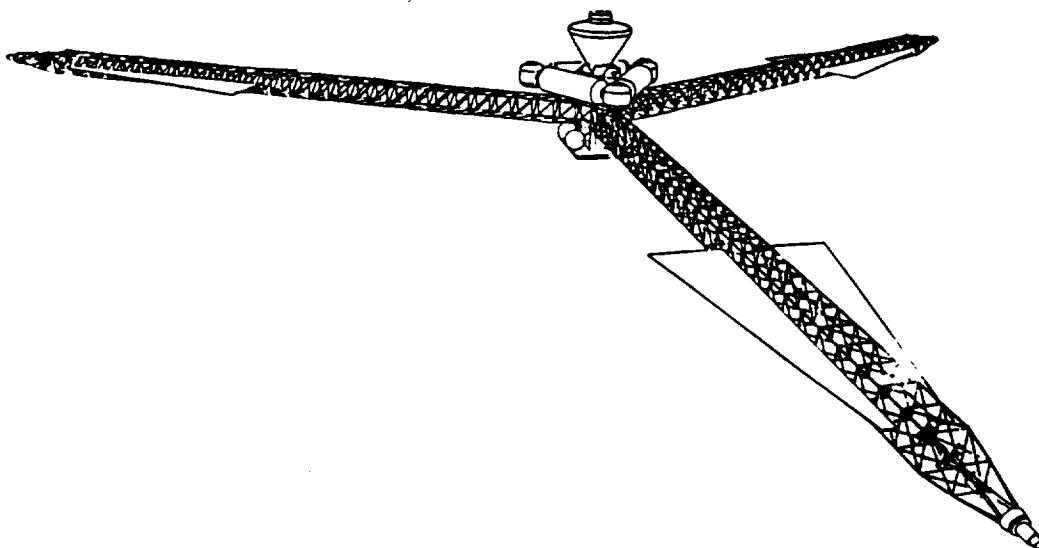
- **PAYOFF**

Provides a 300 W/kg PV blanket; 100 W/kg InP concentrator module, a 100 W-h/kg battery (flight weight), 1 - 2 kg/m² thermal management system with advanced PMAC integrated system and durable high temperature electronics subsystem

NASA NUCLEAR PROPULSION PROGRAM

EAET

Possible Nuclear Electric Propulsion Concept for Advanced Space Missions



Program Goals

- Develop the technologies required to apply space nuclear propulsion systems to improve the mission performance for human missions to Mars
- Identify and develop at least one space nuclear thermal propulsion system and one nuclear electric propulsion system that, alone or in combination with other propulsion systems, meets the propulsion requirements for piloted and cargo missions to Mars (including unmanned precursor missions) and for which technical feasibility issues have been resolved

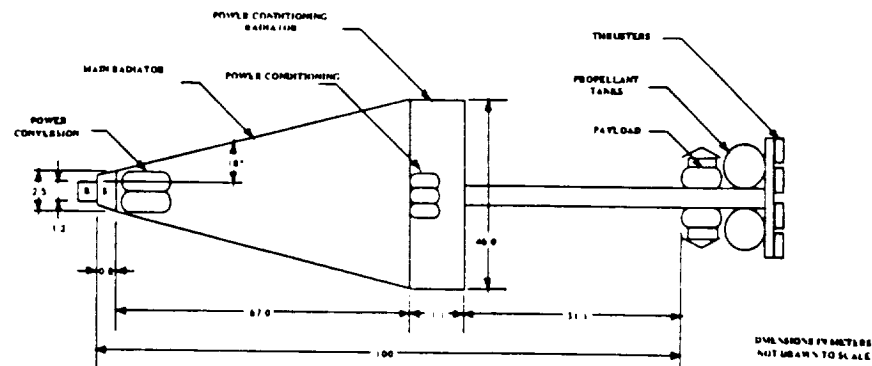
NUCLEAR PROPULSION

NUCLEAR THERMAL PROPULSION

NUCLEAR ELECTRIC PROPULSION

NUCLEAR ELECTRIC PROPULSION

The generic nuclear electric propulsion (NEP) system uses a nuclear reactor to produce electrical power which is then used to operate low-thrust electromagnetic thrusters (such as ion thrusters or magnetoplasmadynamic thrusters). The advantage of NEP is that the specific impulse is increased by a factor of at least 10 and perhaps 20 compared to chemical propulsion which can result in a significant reduction (factor of ~2) of the mass into low Earth orbit. Combined with a high-thrust option (either chemical or nuclear thermal propulsion) it can achieve the same transit times as nuclear thermal propulsion.



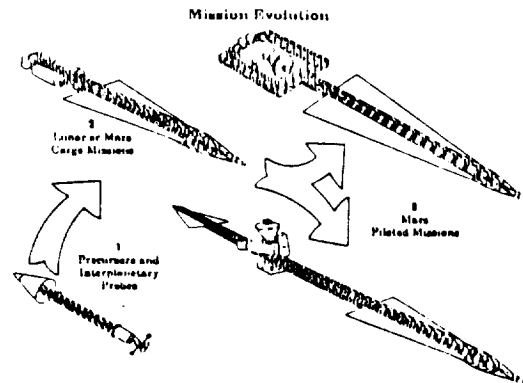
Basic Features of a Nuclear Electric Propulsion System

NEP EVOLUTION POTENTIAL

- NEP MAY EVOLVE FROM kWe POWER LEVELS (SP-100) TO MULTI-MWe POWER LEVELS
- NEAR TERM NEP TECHNOLOGY MAY BE APPLIED TO UNMANNED PLANETARY MISSIONS (e.g. OUTER PLANETS, ASTEROIDS, COMETS) WHICH HAVE HIGH SCIENTIFIC RETURN AS WELL AS LAYING A FOUNDATION FOR THE NEXT STEP OF EVOLUTION
 - HIGHLY ENERGETIC MISSIONS CAN BE PERFORMED WITH NEAR TERM NEP TECHNOLOGY

Characteristics of Nuclear Electric Propulsion

- Powers range from kWe to multi-MWe
- High specific impulse
 - Same thruster can operate at range of specific impulses
 - Reduces propellant mass
 - Decreased resupply and refurbishment masses
- Long system life
 - High level of reusability
- Enhanced flexibility
 - Extended launch window
 - Same vehicle used for multiple opportunities
- Commonality with surface power systems

UNMANNED EXPLORATION MISSIONS
(POTENTIAL)

<u>MISSION</u>	<u>LAUNCH</u>	<u>DURATION</u>	<u>NEP APPLICABILITY</u>
Main Belt Asteroid	~2000	10 years	Enhancing
Asteroid Sample Return	~2000	5 years	Enhancing (Possibly enabling)
Jovian Grand Tour	Post 2000	Variable	Enabling
Saturn Grand Tour	Post 2000	Variable	Enabling
Thousand Astronomical Unit (TAU)	Post 2010	55+ years	Enabling
Comet Nucleus Sample Return	Post 2000	6 years	Enhancing (Possibly enabling)

**NUCLEAR ELECTRIC PROPULSION
HIGH-PRIORITY NEAR-TERM TECHNOLOGIES**
(Identified by Reactor and Propulsion Subpanels)

PROPULSION

- SCALING TO HIGHER POWER
 - Ion Thrusters/MPD Thrusters
- FACILITY UPGRADES
 - Thermal Management/Pumping
- HIGH-TEMPERATURE POWER PROCESSING

POWER

- HIGH-TEMPERATURE, LIGHT-WEIGHT RADIATORS
- HIGH-TEMP, RAD-HARDENED POWER ELECTRONICS
- SYSTEM INTEGRATION, COMPONENT INTERACTION

KEY ISSUE: INCREASE SPECIFIC POWER (kW/kg)

***Coordination and
Interfaces***

SPACE ENERGY CONVERSION R&T

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COORDINATION/INTERFACES

The following is a list of some of the coordination and interfaces involving the NASA Space Energy Conversion R&T Program

Space Technology Interface Group
(STIG) (NASA/USAF)

Interagency Advanced Power Group

Space Photovoltaic Research &
Technology (SPRAT) Conference

Space Electrochemical Research
& Technology (SERT) Conference

High-Frequency Power Distribution
Control Conference

Radioisotope Power Systems
Requirements Workshop

Aerospace Battery Systems
Steering Committee/Battery
Workshop/Systems Review

SP-100 Steering Committee
(SDIO/DOE/USAF/NASA)

SDIO Independent Evaluation Group
and Field Support Team

DoD Advisory/Review Panels
(AFSTC Investment Strategy, SPT-21,
Thermionic Advisory Team, Thermal
Management Steering Committee,
Space Power Technology Interdependency
Group)

Program Office/Industry Briefings
- Earth Observing System (EOS)
- ATDRSS

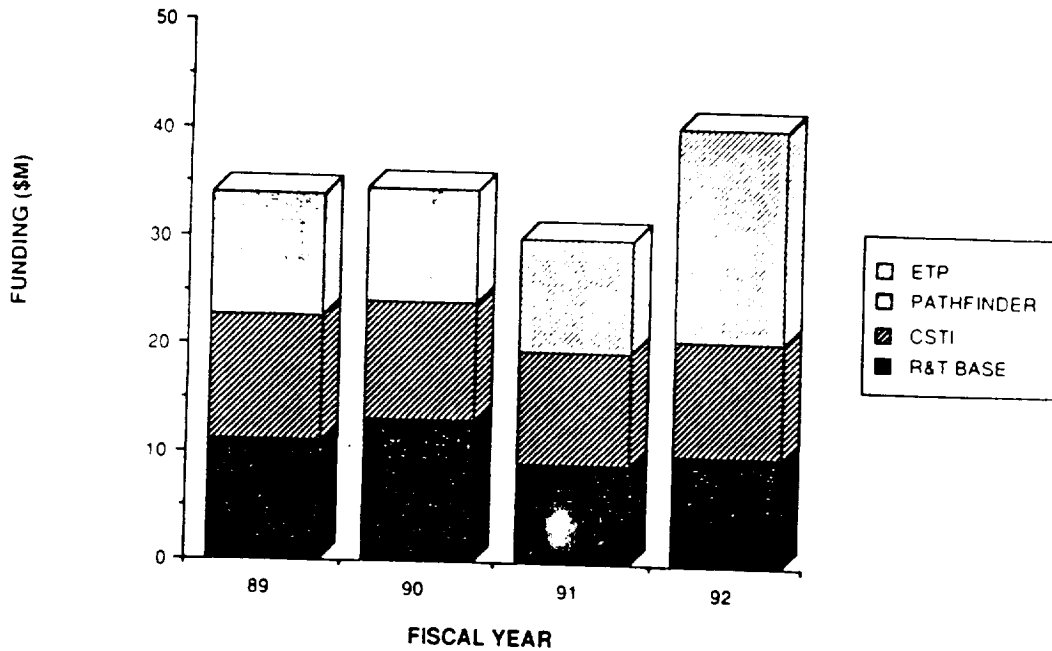
Nuclear Propulsion
(DoD/DOE/NASA)

National Meetings (IECEC, SNPS, etc.)

Budgets

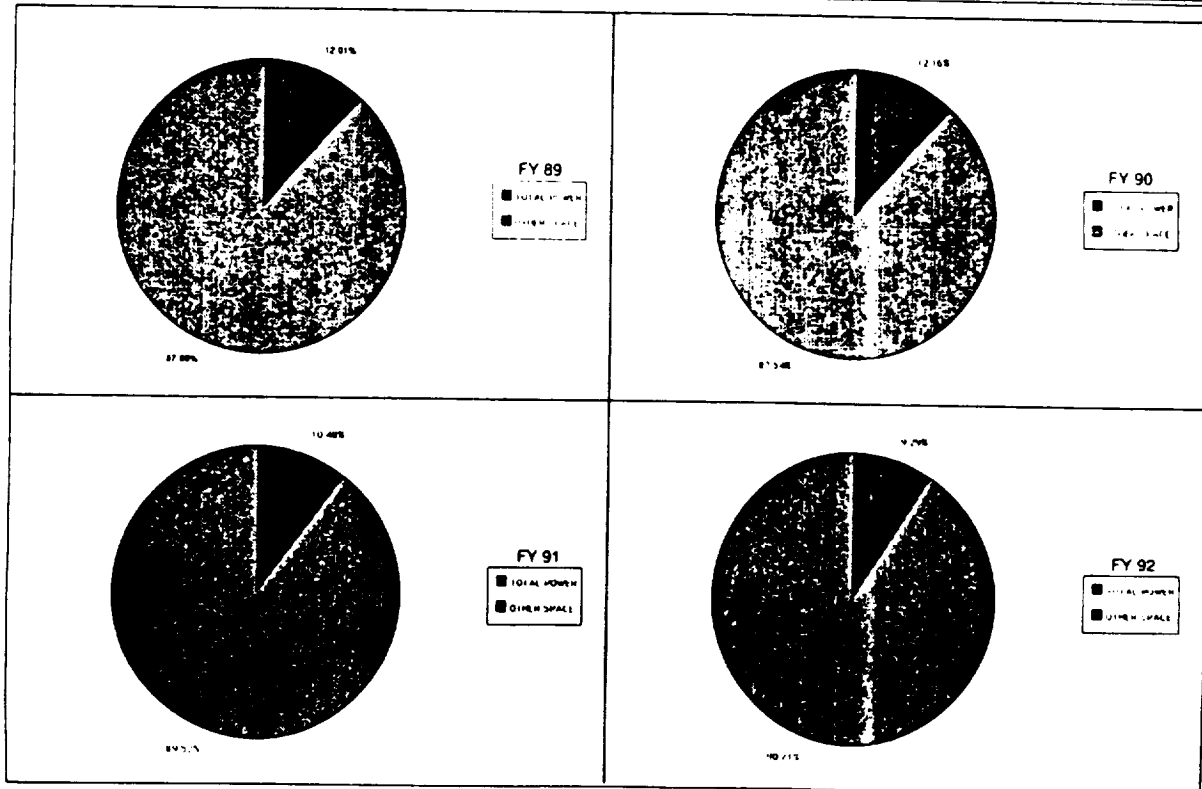
POWER FUNDING TREND

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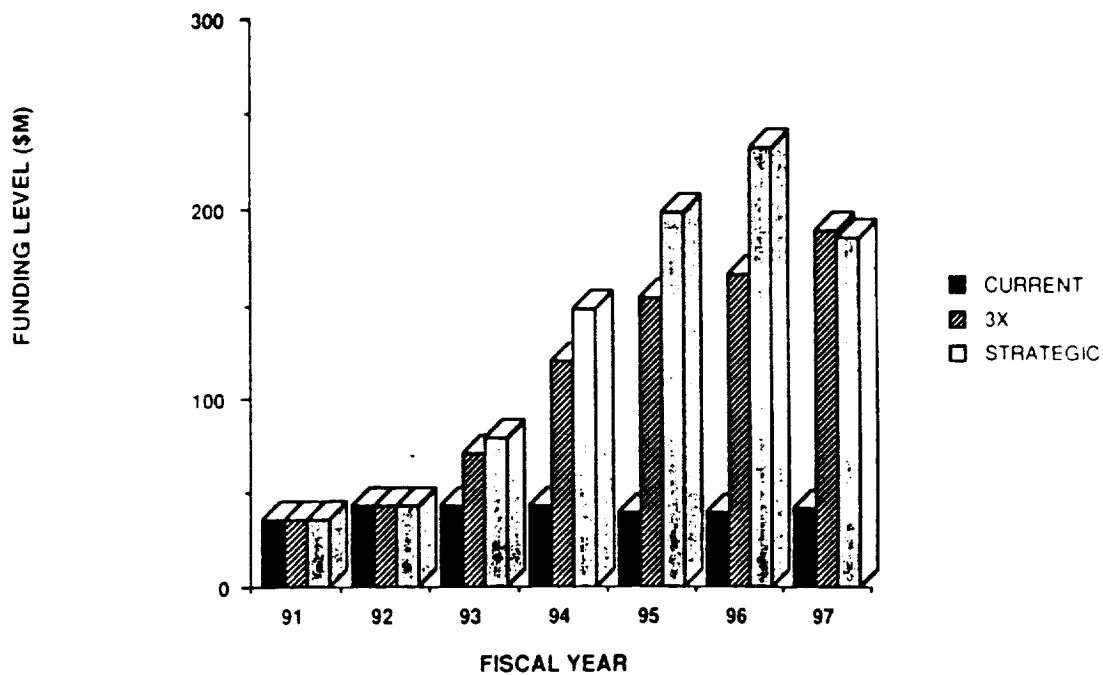
POWER FUNDING TREND AS % OF TOTAL SPACE R&D FUNDING

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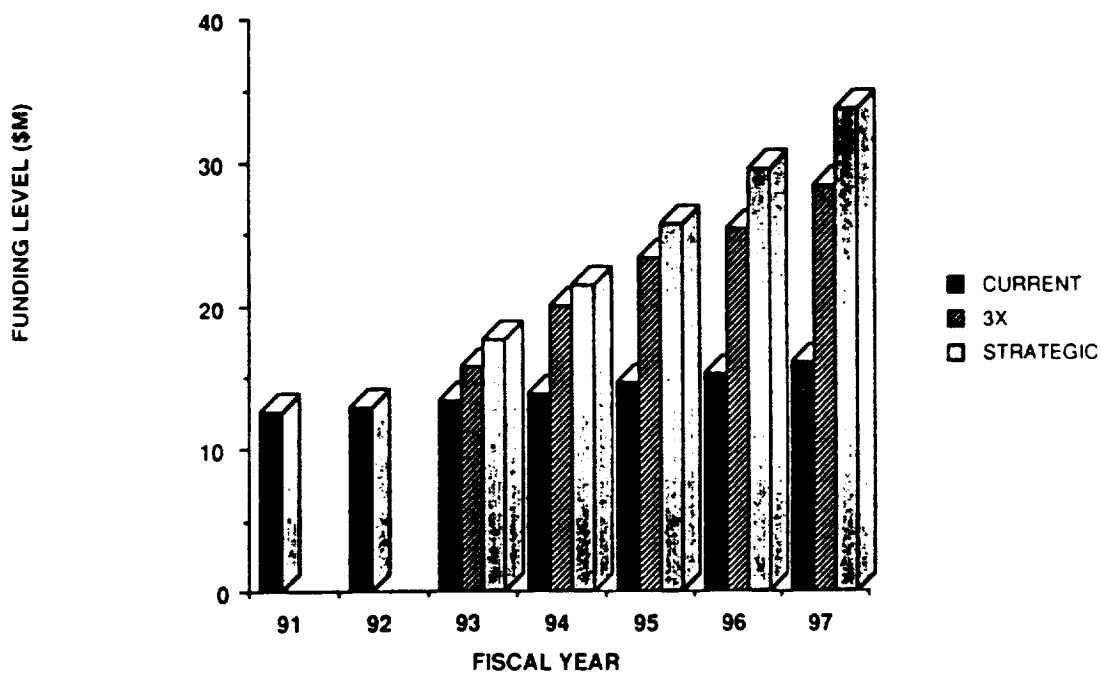
TOTAL SPACE ENERGY CONVERSION TECHNOLOGY

OAET



BASE RESEARCH AND TECHNOLOGY PROGRAM SPACE ENERGY CONVERSION TECHNOLOGY

OAET



WBS No. 506-41 (CURRENT BUDGET)

REVISED 8/11/91

TECHNOLOGY ELEMENT:	POWER R&T				WBS 506-41				CODE RP			
Sub-Element Resources: (\$M)	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
-11 Photovoltaic Energy Conversion	2.4*	2.3	2.4	2.5	2.6	2.7	2.8					
-21 Chemical Energy Conversion	1.8	2.0	2.1	2.2	2.3	2.4	2.5					
-31 Thermal Energy Conversion	1.7	1.4	1.5	1.6	1.7	1.8	1.9					
-41 Power Management	2.0	1.8	1.9	2.0	2.1	2.2	2.3					
-51 Thermal Management	0.7	1.0	1.0	1.1	1.1	1.2	1.2					
Sub-Element Totals: (\$M)	8.6	8.5	8.9	9.4	9.8	10.3	10.7					
CoF:												
CoF Totals:												
Resources Requirements: (\$M)	8.6	8.5	8.9	9.4	9.8	10.3	10.7					
Program Support: (\$M)	1.7	1.8	2.0	2.1	2.3	2.4	2.6					
Special Requirements: (\$M)	2.2	2.5	2.4	2.3	2.5	2.6	2.7					
TOTAL (\$M):	12.5*	12.8	13.3	13.8	14.6	15.3	16.0					

Basis for Resource Estimates:

- Maintain current funding levels; adjust for inflation.

* Includes \$1M carried over from FY90

WBS No. 506-41 ("3X" BUDGET)

REVISED 8/11/91

TECHNOLOGY ELEMENT:	POWER R&T				WBS 506-41				CODE RP			
Sub-Element Resources: (\$M)	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
-11 Photovoltaic Energy Conversion	2.4*	2.3	3.4	5.8	7.2	7.5	8.3					
-21 Chemical Energy Conversion	1.8	2.0	2.9	3.5	3.9	4.4	5.0					
-31 Thermal Energy Conversion	1.7	1.4	1.9	2.1	2.4	2.7	3.0					
-41 Power Management	2.0	1.8	2.9	3.3	3.7	4.1	4.6					
-51 Thermal Management	0.7	1.0	1.1	1.4	1.7	1.9	2.3					
Sub-Element Totals: (\$M)	8.6	8.5	12.2	16.1	18.9	20.6	23.2					
CoF:												
CoF Totals:												
Resources Requirements: (\$M)	8.6	8.5	12.2	16.1	18.9	20.6	23.2					
Program Support: (\$M)	1.7	1.8	1.8	2.0	2.3	2.6	2.8					
Special Requirements: (\$M)	2.2	2.5	1.8	2.0	2.2	2.4	2.6					
TOTAL (\$M):	12.5*	12.8	15.8	20.1	23.4	25.6	28.6					

Basis for Resource Estimates:

- Grow photovoltaic and associated chemical energy storage and power management technologies to make dramatic reductions in spacecraft mass allocated to power.
- Maintain a supporting base activity in thermal energy conversion and thermal management.
- Insufficient resources to develop an advanced concepts technology program as a separate sub-element program. Advanced concepts will be worked in the existing sub-elements.

* Includes \$1M carried over from FY90

WBS No. 506-41 (STRATEGIC BUDGET)

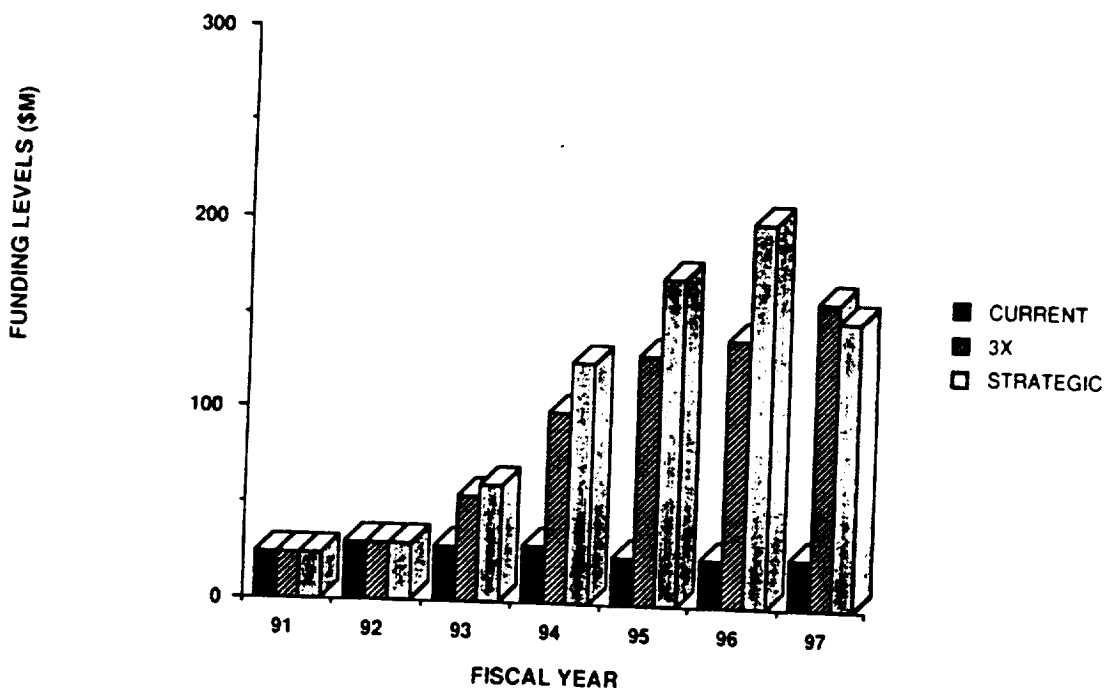
TECHNOLOGY ELEMENT:	POWER R&T				WBS 506-41				CODE RP			
Sub-Element Resources: (\$M)	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
-11 Photovoltaic Energy Conversion	2.4*	2.3	3.3	4.6	5.9	7.2	8.5					
-21 Chemical Energy Conversion	1.8	2.0	2.8	3.4	3.9	4.4	5.0					
-31 Thermal Energy Conversion	1.7	1.4	1.8	2.1	2.4	2.7	3.0					
-41 Power Management	2.0	1.8	2.8	3.2	3.7	4.1	4.6					
-51 Thermal Management	0.7	1.0	1.1	1.4	1.7	1.9	2.3					
-91 Advanced Concepts	0.0	0.0	2.1	2.4	3.2	3.8	4.3					
Sub-Element Totals: (\$M)	8.6	8.5	13.9	17.1	20.8	24.1	27.7					
CoF:												
CoF Totals:												
Resources Requirements: (\$M)	8.6	8.5	13.9	17.1	20.8	24.1	27.7					
Program Support: (\$M)	1.7	1.8	1.8	2.2	2.6	3.0	3.4					
Special Requirements: (\$M)	2.2	2.5	2.0	2.2	2.4	2.6	2.8					
TOTAL (\$M):	12.5	12.8	17.7	21.5	25.8	29.7	33.9					

Basis for Resource Estimates:

- Grow photovoltaic and associated chemical energy storage and power management technologies to make dramatic reductions in spacecraft mass allocated to power.
- Develop advanced concepts program to permit development of innovative technologies that promise revolutionary improvements in performance.
- Maintain a supporting base activity in thermal energy conversion and thermal management.
- Includes \$1M carried over from FY90

FOCUSED TECHNOLOGY PROGRAM SPACE ENERGY CONVERSION TECHNOLOGY

DAET



FOCUSED TECHNOLOGY PROGRAMS SPACE ENERGY CONVERSION R&T

~~CR&T~~

CURRENT BUDGET

PROGRAM ELEMENT	FY91	FY92	FY93	FY94	FY95	FY96	FY97
SPACE NUCLEAR POWER	10	20	25	25	20	20	20.9
HIGH CAPACITY POWER	10.4	10.6	4.5	4.6	4.8	5	5.2
SURFACE POWER & THERMAL MANAGEMENT	0.6	0	0	0	0	0	0
MOBILE SURFACE SYSTEMS	3	0	0	0	0	0	0
LASER POWER BEAMING	0	0	0	0	0	0	0
EARTH ORBITING PLATFORM POWER & THERMAL MANAGEMENT	0	0	0	0	0	0	0
SPACECRAFT POWER & THERMAL MANAGEMENT	0	0	0	0	0	0	0
TOTAL	24	30.6	29.5	29.6	24.8	25	26.1

Basis for Resource Estimates: Maintain current funding levels

FOCUSED TECHNOLOGY PROGRAMS SPACE ENERGY CONVERSION R&T

~~CR&T~~

"3X" BUDGET

PROGRAM ELEMENT	FY91	FY92	FY93	FY94	FY95	FY96	FY97
SPACE NUCLEAR POWER	10	20	25	25	26	27	28
HIGH CAPACITY POWER	10.4	10.6	10.9	12	12.3	12.6	18
SURFACE POWER & THERMAL MANAGEMENT	0.6	0	3.4	9	12.6	14	18
MOBILE SURFACE SYSTEMS	3	0	0	0	0	0	0
LASER POWER BEAMING	0	0	8	40	64.3	70	75
EARTH ORBITING PLATFORM POWER & THERMAL MANAGEMENT	0	0	3.5	6.5	7.5	8	10
SPACECRAFT POWER & THERMAL MANAGEMENT	0	0	0	0	0	0	0
TOTAL	24	30.6	55.6	100.5	131.1	140.5	161

Basis for Resource Estimates: Grow Surf. Pwr/Laser Beaming/E-O Platforms to make dramatic reductions in spacecraft mass allocated to power

FOCUSED TECHNOLOGY PROGRAMS SPACE ENERGY CONVERSION R&T

OARF

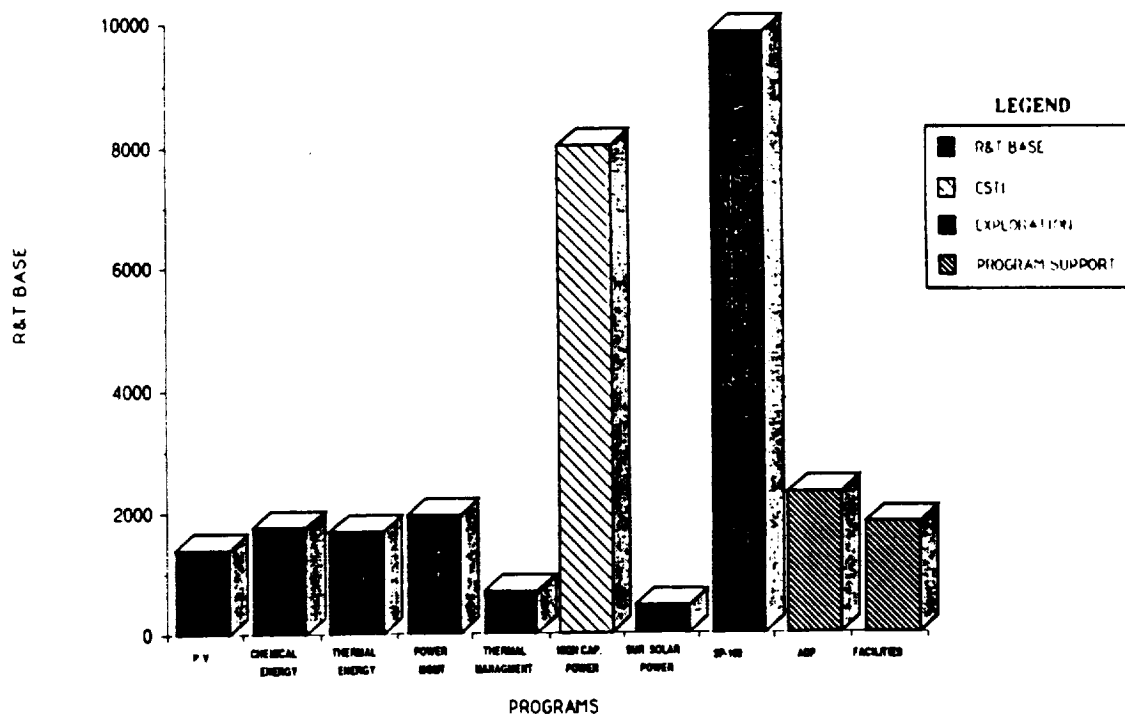
STRATEGIC BUDGET

PROGRAM ELEMENT	FY91	FY92	FY93	FY94	FY95	FY96	FY97
SPACE NUCLEAR POWER	10	20	25	25	26	27	28
HIGH CAPACITY POWER	10.4	10.6	11.1	16.8	23	30.5	23
SURFACE POWER & THERMAL MANAGEMENT	0.6	0	5	11.7	18.5	24.2	25.3
MOBILE SURFACE SYSTEMS	3	0	0	3	3.2	8	10.4
LASER POWER BEAMING	0	0	13.5	56.9	82.5	90.8	41
EARTH ORBITING PLATFORM POWER & THERMAL MANAGEMENT	0	0	5.1	10.2	13.5	14.3	14.7
SPACECRAFT POWER & THERMAL MANAGEMENT	0	0	2	3.5	6	7.5	9.1
TOTAL	24	30.6	61.7	127.1	172.7	202.3	151.5

Basis for Resource Estimates: Grow Surf. Pwr/Laser Beaming/E-O & SC Platforms/Hi Capacity Pwr to make dramatic reductions in platform/base power mass (or increased power)

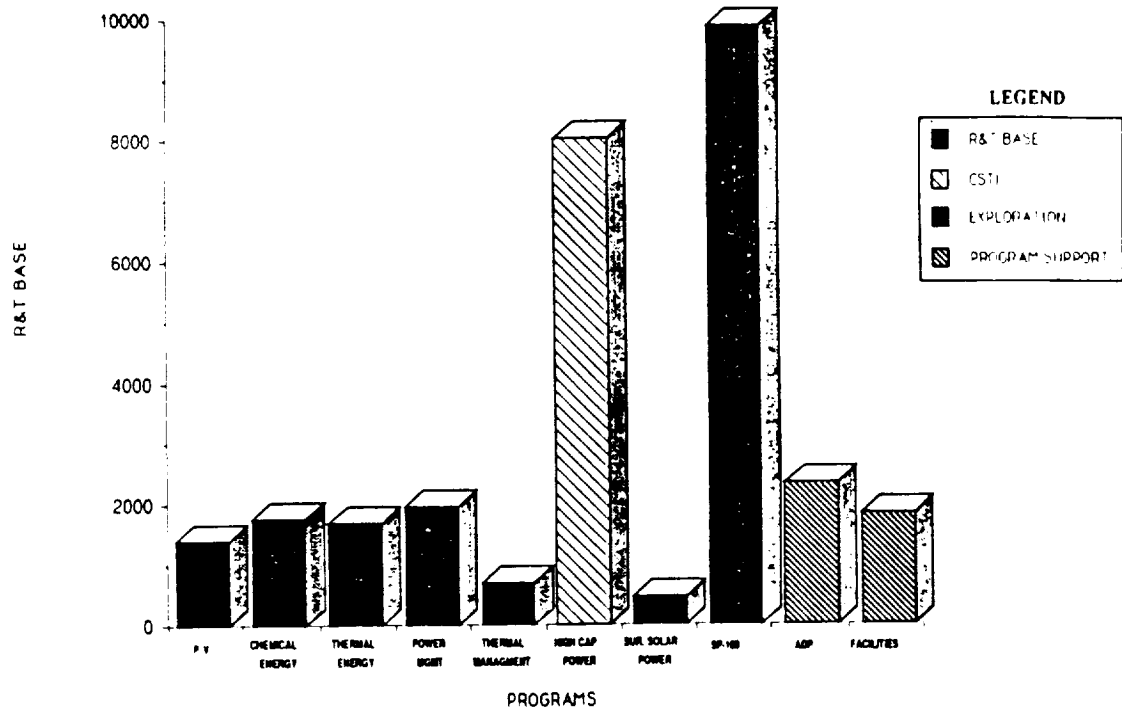
CODE RP POWER FUNDING POWER FUNDS DISTRIBUTION FOR FY 91

OARF



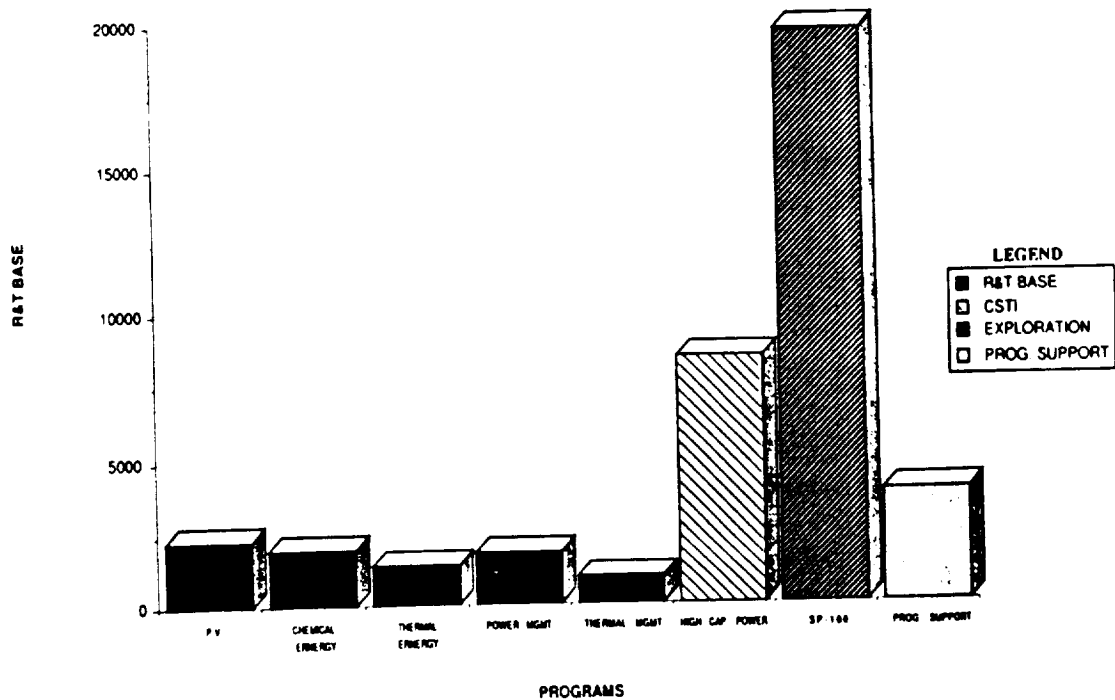
CODE RP POWER FUNDING
POWER FUNDS DISTRIBUTION FOR FY 91

OAE



CODE RP POWER FUNDING
POWER FUNDS DISTRIBUTION FOR FY 92

OAE



Summary

SPACE ENERGY CONVERSION R&T SUMMARY

OAET

- **TECHNICAL CHALLENGE**

To make a 2X to >10X improvement in the performance of space power systems (specific power/energy, efficiency, lifetime, reliability, etc.)
To enable a wide range of future space missions while holding the power mass fraction at or below today's technology

- **APPROACH**

Develop lighter, more efficient primary power sources and energy storage systems with lighter, more reliable, more compact power management & control with innovative thermal management and power distribution.

- **PAYOFF**

This technology will enable future missions to provide the same power at greatly reduced mass or more power from the same mass. More importantly, this technology will enable a host of future SEI and other space missions.

- **RATIONALE FOR AUGMENTATION**

These resources will allow the base technology to be moved out of the laboratory and demonstrated to a degree that users can take it over. These resources will permit work on new technologies focused on future space missions.

- **RELATIONSHIP TO OTHER PROGRAMS**

This work is closely coupled (base + focused) and is well coordinated with other agencies and users.

- **TECHNOLOGY CONTRIBUTIONS**

SSF (PV, NiH₂, SD, Env.), HST (NiH₂), EOS (PV, NiH₂, Therm. mgmt), DoD (NiH₂), GaAs, USAF (Li primary)

External Review Process

INTEGRATED TECHNOLOGY PLAN FOR THE CIVIL SPACE PROGRAM EXTERNAL REVIEW APPROACH

DAFST

OBJECTIVES

***"NASA (SHOULD) UTILIZE AN EXPERT, OUTSIDE REVIEW
PROCESS, MANAGED FROM HEADQUARTERS, TO ASSIST
IN THE ALLOCATION OF TECHNOLOGY FUNDS"***

- **REVIEW THE PROCESS USED FOR DEVELOPING THE
INTEGRATED TECHNOLOGY PLAN FOR THE CIVIL SPACE
PROGRAM**
- **ASSESS THE TECHNICAL CONTENT OF THE PROPOSED ITP**
 - **IDENTIFY KEY TECHNOLOGY AREAS THAT NEED TO BE ADDRESSED**
 - **FIRST-ORDER EVALUATION OF THE ESTIMATES OF "COST FOR
ACCOMPLISHMENT"**
 - **RECOMMEND ADJUSTMENTS IN PRIORITIES AND RESOURCE PLANNING**
- **ASSESS THE ACCOMMODATION OF USER NEEDS**
 - **EVALUATE STRATEGIC AND NEAR-TERM TECHNOLOGY PLANS AGAINST
TECHNOLOGY NEEDS OF FUTURE MISSIONS**
 - **RECOMMEND POTENTIAL CHANGES IN THE PHASING OF NEW PROGRAMS TO
BETTER MEET TECHNOLOGY NEEDS**

**MAY 13, 1991
JCM 7461**

ITP EXTERNAL REVIEW PLANNING

~~OASD~~

~~PRELIMINARY~~

DETAILED REVIEW APPROACH

- PROVIDE OVERVIEWS IN PLENARY SESSION PRESENTATIONS
 - MISSION USER TECHNOLOGY NEEDS AND APPLICATIONS
 - EXTERNAL PERSPECTIVES ON SPACE TECHNOLOGY
 - STRATEGIC OVERVIEW OF INTEGRATED TECHNOLOGY PLAN
- REVIEW THRUSTS PLENARY SESSION
 - SCIENCE, EXPLORATION, TRANSPORTATION, PLATFORMS, & OPERATIONS
- CONDUCT IN-DEPTH REVIEWS AGAINST VERTICALLY-INTEGRATED DISCIPLINE RESEARCH AREAS
 - PARALLEL TO 1987 ASEB STUDY APPROACH
 - ASSESS PLANS/DEVELOP RECOMMENDATIONS USING PANEL CHAIRMAN & RECORDING SECRETARY APPROACH
- CONDUCT SELECTED REVIEWS IN ADDITIONAL SPECIAL TOPIC AREAS
 - RESEARCH AREAS, MANAGEMENT TOPICS
 - ASSESS PLANS/DEVELOP RECOMMENDATIONS USING PANEL CHAIRMAN & RECORDING SECRETARY APPROACH
- CONDUCT DETAILED REVIEW DISCUSSIONS IN AD HOC SESSIONS, TO BE DETERMINED AT THE MEETING; COORDINATE AND REPORT WORKING GROUP RESULTS THROUGH PLENARY SESSION
- DEVELOP SUMMARY RECOMMENDATIONS IN STEERING COMMITTEE SESSION(S)

JUNE
JCM

EXTERNAL REVIEW APPROACH

~~OASD~~

PRODUCT

*A FORMAL REVIEW REPORT, TO BE PUBLISHED WITHIN
60 DAYS OF THE END OF THE MEETING*

- PROGRAMMATIC RECOMMENDATIONS AND/OR ASSESSMENTS REGARDING DISCIPLINE AREAS (INCLUDING BOTH BASE AND FOCUSED PROGRAMS)
 - WHAT ARE THE RIGHT RESEARCH ISSUES, ARE THEY BEING ADDRESSED?
 - WHAT IS THE RIGHT LEVEL OF INVESTMENT, IS IT PROVIDED FOR IN THE ITP?
 - WHAT IS THE RIGHT BALANCE OF RESOURCES ACROSS THE ELEMENTS IN THE AREA (I.E., WHAT ARE THE RIGHT PRIORITIES AND WHY?)
- PROGRAMMATIC RECOMMENDATIONS AND/OR ASSESSMENTS REGARDING TECHNOLOGY THRUSTS
 - WHAT ARE THE RIGHT MISSION NEEDS, ARE THEY BEING ADDRESSED?
 - WHAT IS THE RIGHT LEVEL OF INVESTMENT, IS IT PROVIDED FOR IN THE ITP?
 - WHAT IS THE RIGHT BALANCE OF RESOURCES ACROSS THE ELEMENTS IN THE THRUST? (I.E., WHAT ARE THE RIGHT PRIORITIES AND WHY?)
- PROGRAMMATIC RECOMMENDATIONS AND/OR ASSESSMENTS FOR THE OVERALL PROGRAM
 - ARE THE RIGHT RESEARCH ISSUES AND MISSION NEEDS BEING ADDRESSED?
 - WHAT IS THE RIGHT LEVEL OF INVESTMENT, IS IT PROVIDED FOR IN THE ITP?
 - WHAT IS THE RIGHT BALANCE OF RESOURCES ACROSS THE THRUSTS AND IN THE R&T BASE? (I.E., WHAT ARE THE RIGHT PRIORITIES AND WHY?)

MAY 14 1991
JCM 7465

SPACE ENERGY CONVERSION R&T

~~SECRET~~

REVIEW QUESTIONS

- Is the program content/approach correct?
- Is the level of investment correct?
- Given the available funding are the priorities correct?
- Is the user interface functioning properly?
- Are the efforts being properly coordinated?
- Are the user needs being met?
- Are the participants correct?
- Is the R&T Base content innovative enough to provide improved capability for future user/mission applications?
- Does the R&T Base activity maintain or enhance NASA's technical capabilities?

Backup Material

PHOTOVOLTAIC ENERGY CONVERSION

TECHNOLOGY NEEDS

- THE HIGH PERFORMANCE PHOTOVOLTAIC ENERGY CONVERSION PROGRAM WILL DEVELOP TECHNOLOGY THAT CAN SUPPORT A WIDE RANGE OF EARTH ORBITING AND INTERPLANETARY MISSIONS INCLUDING:
 - SPACE STATION
 - REDUCES ARRAY AREA BY $\geq 1/2$
 - EARTH OBSERVING SYSTEM
 - LONG LIFE, LIGHT-WEIGHT, RADIATION-HARD ARRAY
 - LUNAR/MARS SURFACE POWER
 - COMPACT, TRANSPORTABLE ARRAYS
 - ELECTRIC PROPULSION
 - LEO-GEO AND INTERPLANETARY
 - COMMUNICATIONS SATELLITES
 - ALL NEAR-EARTH MISSIONS

CHEMICAL ENERGY CONVERSION

TECHNOLOGY NEEDS

- THE CHEMICAL ENERGY CONVERSION AND STORAGE TECHNOLOGY PROGRAM WILL SUPPORT EMERGING PLANETARY AND SCIENCE MISSIONS DEMANDING HIGH SPECIFIC ENERGY (3X STATE OF THE ART) AND LONG-LIFE RECHARGEABLE BATTERIES, INCLUDING
 - PLANETARY SPACECRAFT
 - RECHARGEABLE LITHIUM, NICKEL-HYDROGEN SYSTEMS OR ADVANCED
 - SURFACE EXPLORERS/ROVERS
 - RECHARGEABLE LI, NIH₂, FUEL CELLS OR ADVANCED CONCEPTS
 - LUNAR/MARS SURFACE POWER
 - REGENERATIVE FUEL CELLS
 - PENETRATORS
 - RECHARGEABLE LITHIUM
 - ALL NEAR-EARTH MISSIONS (ATDRSS/EOS/SATCOMS/SSF SHUTTLE EMAs)
 - PENETRATORS

THERMAL ENERGY CONVERSION

TECHNOLOGY NEEDS

- THE THERMAL ENERGY CONVERSION PROGRAM WILL PROVIDE THE ENHANCING AND ENABLING TECHNOLOGIES FOR:
 - SPACE STATION
 - LIGHT-WEIGHT, LOWER COST, HIGH PERFORMANCE SOLAR DYNAMIC
 - SURFACE EXPLORERS/ROVERS
 - RADIOISOTOPE THERMOELECTRIC GENERATORS OR AMTEC
 - LUNAR SURFACE POWER
 - LUNAR MATERIAL FOR THERMAL ENERGY STORAGE
 - PROBES AND PENETRATORS
 - RTGs and AMTEC
 - DEEP SPACE ORBITAL AND FLYBY MISSIONS (INCLUDING ELECTRIC PROPULSION)
 - RTGs, AMTEC, and REACTORS

POWER MANAGEMENT

TECHNOLOGY NEEDS

- THE POWER MANAGEMENT TECHNOLOGY PROGRAM WILL SUPPORT TECHNOLOGIES FOR CONDITIONING, DISTRIBUTION AND CONTROL OF ELECTRICAL POWER FOR THE FULL RANGE OF SPACE AND PLANETARY MISSIONS, INCLUDING:
 - EARTH OBSERVING SYSTEMS
 - INCREASED POWER DENSITY
 - SURFACE EXPLORERS/ROVERS
 - REDUCED VOLUME/SMART PMAD/LASER POWER BEAMING
 - LUNAR/MARS SURFACE POWER
 - AUTONOMOUS OPERATION OF COMPLEX SYSTEM IN HOSTILE ENVIRONMENT/LASER POWER BEAMING
 - PROBES AND PENETRATORS
 - REDUCED VOLUME/INCREASED POWER DENSITY/HOSTILE ENVIRONME
 - DEEP SPACE ORBITAL AND FLYBY MISSIONS (INCLUDING ELECTRIC PROPULSION)
 - REDUCED VOLUME/AUTONOMOUS OPERATION/HOSTILE ENVIRONMEN

THERMAL MANAGEMENT

TECHNOLOGY NEEDS

- THE THERMAL MANAGEMENT PROGRAM WILL PROVIDE HIGHLY ADVANCED THERMAL MANAGEMENT TECHNOLOGIES TO ENABLE:
 - LOW MASS SPACE RADIATORS
 - IMPORTANT FOR ALL PLANETARY AND SPACE MISSIONS
 - RADIATOR SIZE REDUCTIONS FOR SPACE POWER ELECTRONICS
 - IMPORTANT FOR ALL SPACECRAFT AND BASES
 - THERMAL CONTROL FOR SPACECRAFT INSTRUMENTS, SENSORS, AND OTHER HEAT DISSIPATING EQUIPMENT
 - IMPORTANT FOR ALL SPACECRAFT AND BASES

SPACE ENERGY CONVERSION R&T

FOCUSED POWER PROGRAMS THAT AFFECT THE BASE

- SPACE PLATFORMS
 - PLANAR AND CONCENTRATOR ARRAYS IMMUNE TO SPACE ENVIRONMENT
 - IMPROVED BATTERY SYSTEMS (APPROACHING 150 Wh/kg)
 - INTEGRATED, HIGH-EFFICIENCY POWER MANAGEMENT & CONTROL THAT IS HIGHLY AUTONOMOUS (GOAL: 2X REDUCTION IN MASS)
 - HIGH EFFICIENCY (2X - 4X IMPROVEMENT) CONVERSION SYSTEMS FOR DEEP SPACE MISSIONS
 - INTEGRATED THERMAL MANAGEMENT/HIGH TEMPERATURE ELECTRON TO YIELD 3X REDUCTION IN SPACECRAFT BUS MASS
- EXPLORATION (SURFACE POWER/MOBILE SURFACE POWER)
 - HIGH-EFFICIENCY CONVERSION SYSTEMS (e.g., STIRLING, T/E)
 - HIGH ENERGY DENSITY STORAGE (REGEN. FUEL CELLS/BATTERIES)
 - THERMAL MANAGEMENT
 - LASER POWER BEAMING

OSO TECHNOLOGY NEEDS

OAEI

HIGHEST-PRIORITY

High-Rate Communications

Optical and Millimeter Wave Radio Frequencies
(for space-to-ground and space-to-space)

Advanced Data Systems

Advanced Data Storage, Data Compression, and
Information Management Systems

Advanced Navigation Techniques

New techniques for cruise, approach,
and in-orbit navigation

Mission Operations

Artificial Intelligence, Expert Systems, Neural
Networks, Increased Automation in Mission Operations,
Testbeds for Advanced Software, Coordination of
Distributed Software, and Automated Performance
Analysis of Networking Computing Environments

LBF40304a
(JCM 6843a)

OSF TECHNOLOGY NEEDS

OAEI

HIGHEST-PRIORITY

Program Unique Requirements

Vehicle Health Management
Advanced Turbomachinery (Components/Models)
Combustion Devices
Advanced Heat Rejection Technologies
High-Efficiency Space Power Systems
Water Recovery and Management
Advanced Extravehicular Mobility Unit
Electromechanical Control Systems
Crew Training Systems
Characterization of Al-Li Alloys
Cryogen Storage, Handling & Supply
TPS for High-Temp. Applications
Robotic Systems
Orbital Debris
Guidance, Navigation & Control
Advanced Avionics Architectures

Industry Driven Technologies

Signal Transmission and Reception
Advanced Avionics Software
Video Technologies
Environ. Safe Cleaning Solvents, Refrig./Foams
Non-Destructive Evaluation

LBF40302a
(JCM 6835a)

INTEGRATED TECHNOLOGY PLAN FOR THE CIVIL SPACE PROGRAM

MFPE/SEI TECHNOLOGY NEEDS

OAET

HIGHEST-PRIORITY

Category 1

Radiation Protection
EVA Systems
Nuclear Thermal Propulsion
Regenerative Life Support
Cryo. Fluid Mgt. Storage & Transfer
Micro-G Countermeasures/Art. Gravity
Aerobraking

Category 2

Auto. Rendezvous & Docking
Health Maintenance & Care
In-Space Systems Assy/Processing
Surface Systems Construction/Processing
Cryogenic Space Engines
In Situ Resource Utilization
Surface Power

Category 3

Autonomous Landing
Human Factors
Surface System Mobility & Guidance
Electric Propulsion
Sample, Acquisition, Analysis & Preserv.

LBF40301a
(JCM 6836a)

INTEGRATED TECHNOLOGY PLAN FOR THE CIVIL SPACE PROGRAM

Space Exploration Initiative Technology Needs

OAET

HIGHEST-PRIORITY

Category 1

Radiation Protection
EVA Systems
Nuclear Thermal Propulsion
Regenerative Life Support
Cryo. Fluid Mgt. Storage & Transfer
Micro-G Countermeasures/Art. Gravity
Aerobraking

Category 2

Auto. Rendezvous & Docking
Health Maintenance & Care
In-Space Systems Assy/Processing
Surface Systems Construction/Processing
Cryogenic Space Engines
In Situ Resource Utilization
Surface Power

Category 3

Autonomous Landing
Human Factors
Surface System Mobility & Guidance
Electric Propulsion
Sample, Acquisition, Analysis & Preserv.

LBF40303a
(JCM 6836a)

INTEGRATED TECHNOLOGY PLAN FOR THE CIVIL SPACE PROGRAM

Office of Space Science and Applications

	NEAR-TERM NEED	MID-TERM NEED	FAR-TERM NEED
HIGHEST PRIORITY	<ul style="list-style-type: none"> Sub-mm & μ-wave Sensing Long Life Cryo Coolers/Cryo Shielding High Energy Detectors Sensor Readout Electronics Vibration Isolation Technology Efficient/Quiet Refrigerator/Freezer Extreme Upper Atmosphere Instr. Platforms 	<ul style="list-style-type: none"> Long Life, Stable, Tunable Lasers Solar Probe/Mercury Orbiter Thermal Protect. High Vol./Density/Rate Onboard Data Storage Interferometer Specific Technology 	<ul style="list-style-type: none"> Structures: Large/Controlled/Deployed/Ant'a Robotics Precision Inter. S/C Ranging/Positioning 50-100 Kilowatt Ion Propulsion (NEP) Large Filled Apertures Parallel S/W Env. for Model&Data Visualization Computational Techniques
2ND HIGHEST PRIORITY	<ul style="list-style-type: none"> High Frame Rate/Res. Video/Data Compress 2.4 to 4 Meter 100 K Lightweight PSR Solar Arrays/Cells Automated Biomedical Analysis Radiation Hardened Parts/Detectors Long Life/High Energy Density Batteries Real Time Environmental Control Space Qualified Masers/Ion Clocks Fluid Diagnostics 	<ul style="list-style-type: none"> Auto Sequencing & CMD Generation Auto S/C Monitoring & Fault Recovery 32 GHz TWT/Optical Communications Telescience/Telepresence/Art. Intelligence Improved EVA Suit/PLSS (EMU) Combustion Devices Plasma Wave Antenna/Thermal 	<ul style="list-style-type: none"> SIS 3 THz Heterodyne Receiver SETI Detector Technologies Mini Ascent Vehicle/Lander Deceleration Radiation Shielding for Crews SAAP/Probes/In Situ Instr./s/Penetrators Human Artificial Gravity Systems X Ray Optics Technology Returned Sample/Biohazard Analysis Cap High Resolution Spectrometer
3RD HIGHEST PRIORITY	<ul style="list-style-type: none"> Descent Imaging/Mini RTG/Mini Camera K Band Transponders Ultra High Gigabit/sec Telemetry Mini Spacecraft Subsystems Real Time Radiation Monitoring Solid/Liquid Interface Characterization Laser Light Scattering High Temperature Melts for Furnaces Field Portable Gas Chromatographs Adv. Furnace Technology 	<ul style="list-style-type: none"> Regenerative Life Support Thermal Control System Non Contact Temp. Measurement 3-D Packaging for 1MB Solid State Chips Microbial Decontamination Methods Animal and Plant Reproduction Aids Special Purpose Bioreactor Simulator Syst Rapid Subject/Sample Delivery & Return Capability 	<ul style="list-style-type: none"> Autonomous Rendezvous/Sample Xfer/Landing Non Destructive Monitoring Capability Low Drift Gyros/Trackers/Actuators Heat Shield for 16 km/sec Earth entry Partial G/j G Medical Care Systems Dust Protection/Jupiter's Rings Non Destructive Cosmic Dust Collection CELSS Support Technologies

LBF40301
(JCM 6034)

ORIGINAL PRINT IS
OF POOR QUALITY

SPACE PHOTOVOLTAIC ENERGY CONVERSION

PRESENTED
AT THE
ITP EXTERNAL REVIEW

McLEAN VIRGINIA
JUNE 26, 1991

DENNIS J. FLOOD
LEWIS RESEARCH CENTER

SPACE ENERGY TECHNOLOGY SPACE ENERGY CONVERSION

== OAET ==

PHOTOVOLTAICS

OBJECTIVES

- Programatic
Develop and Demonstrate High Efficiency Lightweight,
Long Life, Durable Photovoltaic Cell and Array Technology
- Technical
 - ≥300 W/kg Planar Array Technology
 - ≥330 W/m² Conc. Arrays
 - ≤ 1% Cell Degradation, 10 Years GEO
 - ≥1000 W/kg Flexible Blanket

SCHEDULE (Strategic Budget)

- 1992 12-panel APSA
- 1993 Conc. Array Preliminary Design
- 1994 Demonstrate Thin 20% InP Cell
- 1995 Demonstrate High-Temperature Blanket
- 1996 Demonstrate >10% CIS Flexible Blanket
- 1997 Demonstrate Blanket for 300 W/kg Array
- 1998 Demonstrate 2nd Generation APSA
- 1999 Ground Test 330 W/m² 1 kW Concentrator Array

RESOURCES(M\$)

	CURRENT	3X	STRATEGIC
● 1991	2.4	2.4	2.4
● 1992	2.3	2.3	2.3
● 1993	2.4	3.4	3.3
● 1994	2.5	5.8	4.6
● 1995	2.6	7.2	5.9
● 1996	2.7	7.5	7.2
● 1997	2.8	8.8	8.5

PARTICIPANTS

- LEWIS RESEARCH CENTER
Advanced Cell and Blanket Technology
- JPL
Lightweight Arrays

SPACE ENERGY TECHNOLOGY SPACE ENERGY CONVERSION

OAET

PHOTOVOLTAICS

OBJECTIVES

- Programatic
Develop and Demonstrate High Efficiency Lightweight,
Long Life, Durable Photovoltaic Cell and Array Technology
- Technical
 - ≥300 W/kg Planar Array Technology
 - ≥330 W/m² Conc. Arrays
 - ≤ 1% Cell Degradation, 10 Years GEO
 - ≥1000 W/kg Flexible Blanket

SCHEDULE (Current Budget)

- 1992 LILT Degradation Mechanism/Solution Determined
- 1993 Amorphous Silicon Radiation Damage Studies Complete
- 1994 Demonstrate Low Temp. Deposition of CIS Cells on Flexible Blanket Material
- 1995 Demonstrate >19% InP Cell on Foreign Substrate
- 1996 Fabricate APSA Thin Film Cell Flexible Blanket
- 1997 Fabricate Blanket for 300 W/kg Array

RESOURCES(M\$)

	CURRENT	3X	STRATEGIC
● 1991	2.4	2.4	2.4
● 1992	2.3	2.3	2.3
● 1993	2.4	3.4	3.3
● 1994	2.5	5.8	4.6
● 1995	2.6	7.2	5.9
● 1996	2.7	7.5	7.2
● 1997	2.8	8.8	8.5

PARTICIPANTS

- LEWIS RESEARCH CENTER
Advanced Cell and Blanket Technology
- JPL
Lightweight Arrays

SPACE SCIENCE TECHNOLOGY PHOTOVOLTAICS

TECHNOLOGY NEEDS

- SUPPORTS A BROAD SPECTRUM OF PLANNED AND FUTURE NASA/DOD/COMMERCIAL MISSION POWER REQUIREMENTS
 - SPACE STATION
 - EOS
 - LUNAR/MARS SURFACE POWER
 - EP/ORBIT TRANSFER, INTERPLANETARY TO 8 AU
 - COMSATS
 - BRILLIANT EYES
 - ALL NEAR EARTH MISSIONS

SPACE SCIENCE TECHNOLOGY PHOTOVOLTAICS

TECHNOLOGY CHALLENGES/APPROACH

- TECHNOLOGY DEVELOPMENT CHALLENGES:
 - EXTEND MISSION LIFE
 - REDUCE ARRAY MOMENT OF INERTIA (i.e., MASS & AREA)
 - REDUCE COST
- TECHNOLOGY DEVELOPMENT APPROACH:
 - BASE R&T ON CELLS & ARRAY CONCEPTS
 - FOCUSSED DEVELOPMENT OF HIGH EFFICIENCY, LIGHTWEIGHT, CONCENTRATOR ARRAY
 - COORDINATE PLANNING & IMPLEMENTATION WITH PROSPECTIVE USERS, (e.g., SSF, EOS, SEI, DOD, etc.)

ITP91-010.4

SPACE ENERGY TECHNOLOGY SPACE ENERGY CONVERSION

== OAET

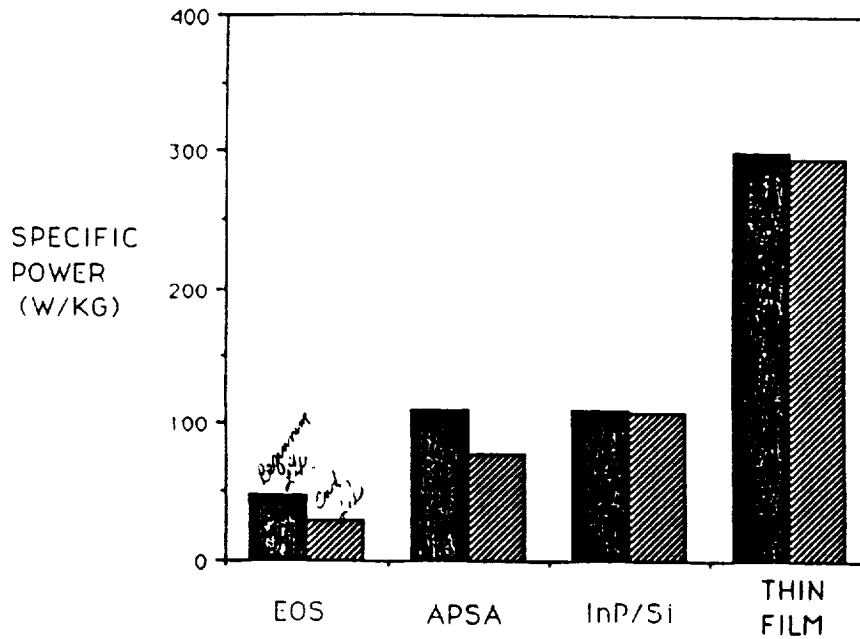
PHOTOVOLTAIC ENERGY CONVERSION TECHNOLOGY BENEFITS

- 3X HIGHER SPECIFIC POWER
+ 30 W/KG SOA TO > 300 W/KG ADV. PLANAR
- 10X HIGHER POWER DENSITY
+ 110 W/SQ.M TO > 330 W/SQ.M
- 20X BETTER RADIATION RESISTANCE
+ > 20% TO < 1%, 10 yrs GEO

SPACE ENERGY TECHNOLOGY SPACE ENERGY CONVERSION

OAET

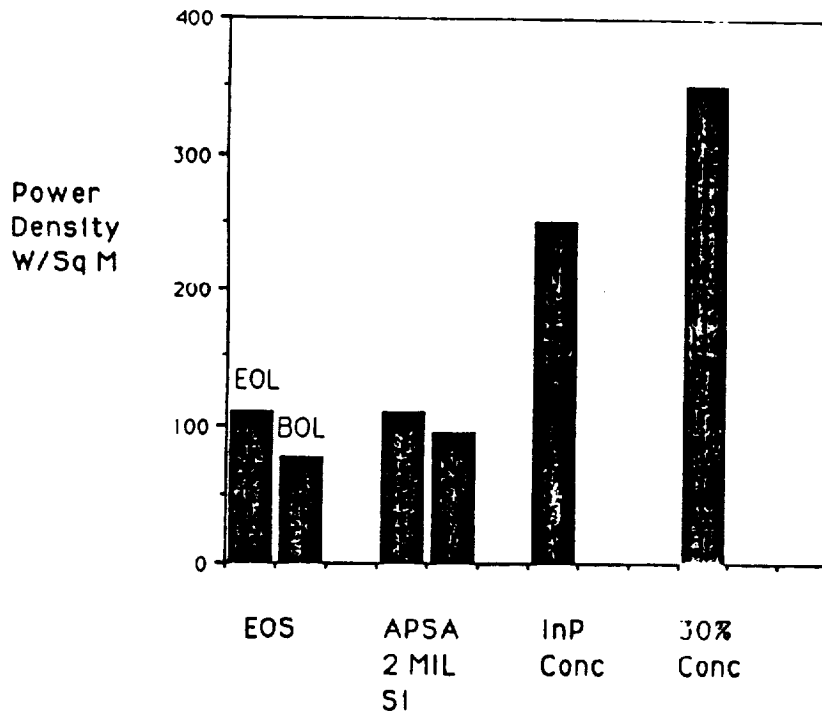
EVOLUTION OF ARRAY SPECIFIC POWER



SPACE ENERGY TECHNOLOGY SPACE ENERGY CONVERSION

OAET

Evolution of Array Power Density



SPACE SCIENCE TECHNOLOGY PHOTOVOLTAICS

STATE-OF-THE-ART ASSESSMENT

- CURRENT:**
- BODY MOUNTED OR DEPLOYABLE RIGID
 - DEPLOYABLE FLEXIBLE ARRAYS
 - NO CONCENTRATOR ARRAYS
 - **Si PLANAR CELLS**
 - 110 W/m², 25 - 40 W/kg
 - 25% - 40% DEGRADATION, 7 YEARS GEO
(2 mil Si CELL @ 15% DEGRADATION)
 - **GaAs PLANAR CELLS**
 - ≥170 W/m², 25 - 40 W/kg
 - 15% DEGRADATION, 10 YEARS GEO
 - **OAET/APSA (ADVANCED PHOTOVOLTAIC SOLAR ARRAY)**
 - 2 mil Si CELL
 - 110 W/m², 130 W/kg
 - 20% DEGRADATION, 10 YEARS GEO

ITP91-010.5

SPACE ENERGY TECHNOLOGY SPACE ENERGY CONVERSION

OAET

HIGH PERFORMANCE PHOTOVOLTAIC SOLAR ARRAYS

CURRENT PROGRAM

- o **ADVANCED PHOTOVOLTAIC SOLAR ARRAY (APSA)**
 - COMPLETE FABRICATION AND VERIFICATION OF 12 PANEL LIGHTWEIGHT PROTOTYPE ARRAY WING
 - DEVELOP DESIGN MODIFICATIONS FOR RETRACTION AND RELATCHING
 - DEVELOP ALTERNATIVE CIRCUIT DESIGNS FOR SHADOWING AND CELL BREAKAGE
- o **RADIATION EFFECTS ON LIGHTWEIGHT BLANKET COMPONENTS**
 - DETERMINE PROTON AND ELECTRON DAMAGE EQUIVALENCE FOR GaAs/Ge SOLAR CELLS
 - CALCULATE GaAs/Ge CELL BEHAVIOR FOR POTENTIAL MISSION APPLICATIONS
- o **LOW INTENSITY, LOW TEMPERATURE (LILT) EFFECTS**
 - DETERMINE MECHANISM FOR LILT DEGRADATION IN SILICON
 - DETERMINE METHOD(S) FOR AVOIDING LILT DEGRADATION

SPACE ENERGY TECHNOLOGY
SPACE ENERGY CONVERSION

OAET

R&T BASE PROGRAM

HIGH PERFORMANCE PHOTOVOLTAIC SOLAR ARRAYS

PERFORMANCE OBJECTIVES

PERFORMANCE REQUIREMENT	CURRENT FLIGHT SOA	SAE	APSA	FUTURE OBJECTIVE
SPECIFIC POWER (w/kg)	30-40	65	130	300
WING POWER LEVEL (kw)	0.2-3.0	3-15	3-15	3-250
LIFETIME (years)	5-10	5-10	10-15	15-20

highperf

SPACE ENERGY TECHNOLOGY
PHOTOVOLTAIC ENERGY CONVERSION

CURRENT PROGRAM

- PERFORMANCE VERIFICATION AND CELL FUNDAMENTALS
 - HIGH ALTITUDE AND LABORATORY SIMULATOR CELL MEASUREMENTS
 - THERMAL CYCLING
 - RADIATION DAMAGE STUDIES
- HETEROEPITAXIAL InP SOLAR CELLS
 - DEVELOP $\geq 17\%$ RADIATION RESISTANT InP CELL ON LOW COST, LIGHTWEIGHT SUBSTRATE
- CONCENTRATOR ARRAY TECHNOLOGY
 - DEMONSTRATE KEY COMPONENT TECHNOLOGY FOR $\geq 300 \text{ W/m}^2$ ARRAY
 - COMPLETE TESTS OF PASP-PLUS FLIGHT HARDWARE
- THIN FILM CELL R&T
 - DEMONSTRATE CIS TECHNOLOGY FOR 1000 W/kg FLEXIBLE SOLAR BLANKET
- SELECTIVE EMITTER/PV CONVERTER R&T
 - DEMONSTRATE KEY TECHNOLOGIES FOR $\geq 20\%$ DIRECT THERMAL-TO-ELECTRIC CONVERSION
- HIGH EFFICIENCY InP CELLS
 - DEMONSTRATE $\geq 20\%$ EFFICIENT PLANAR CELL

SPACE ENERGY TECHNOLOGY PHOTOVOLTAIC ENERGY CONVERSION

InP ON FOREIGN SUBSTRATE PERFORMANCE OBJECTIVES

<u>PERFORMANCE REQUIREMENT</u>	<u>CURRENT SOA</u>	<u>DEVELOPMENT GOALS</u>
CELL EFFICIENCY	10%	≥ 19%
DEGRADATION (10 YEARS GEO)	4%	< 1%
ARRAY SPECIFIC POWER (W/kg)		
BOL	96	380
10 YEARS GEO	92	376
ARRAY SPECIFIC AREA (W/m ²)		
BOL	82	160
10 YEARS GEO	79	158
APPROXIMATE NEED DATE		1995

ITP91-010.6

SPACE SCIENCE TECHNOLOGY PHOTOVOLTAICS

CIS BLANKET PERFORMANCE OBJECTIVE

<u>PERFORMANCE REQUIREMENT</u>	<u>PRESENT SOA</u>	<u>DEVELOPMENT GOALS</u>
CELL EFFICIENCY	11% * (RIGID SUBSTRATE)	≥ 11% (FLEXIBLE SUBSTRATE)
CELL DEGRADATION (10 YEARS GEO)	5% (ESTIMATED)	≤ 1%
BLANKET SPECIFIC POWER		
BOL	24 W/kg *	≥ 1000 W/kg *
10 YEARS GEO	23 W/kg *	≥ 990 W/kg *
BLANKET SPECIFIC AREA		
BOL	135 W/m ² *	135 W/m ² *
10 YEARS GEO	110 W/m ² *	133 W/m ² *
APPROXIMATE NEED DATE		1996

* ESTIMATED FROM TERRESTRIAL MEASUREMENT (NO SPACE CALIBRATED STANDARD AVAILABLE)

ITP91-010.6

SPACE ENERGY TECHNOLOGY SPACE ENERGY CONVERSION

CONCENTRATOR ARRAY TECHNOLOGY PERFORMANCE OBJECTIVES MINI-DOME FRESNEL LENS CONCENTRATOR ARRAY

<u>PERFORMANCE REQUIREMENT</u>	<u>SOA REFLECTIVE CONCENTRATOR SYSTEMS</u>	<u>DEVELOPMENT GOALS MINI-DOME TECHNOLOGY</u>
CONCENTRATOR ELEMENT EFFICIENCY	80 - 90%	> 95%
CONCENTRATOR ELEMENT MATERIAL	METALLIC REFLECTORS	POLYMERIC MATERIALS
PHOTOVOLTAIC CELL EFFICIENCY	18 - 20%	30%
ARRAY LIFETIME	10 YEARS (GEO)	10 YEARS (GEO)
COST	HIGH	LOW *
ARRAY SPECIFIC POWER (W/kg)	25 - 40	> 100
ARRAY SPECIFIC AREA (W/m ²)	160 - 180	> 330
APPROXIMATE NEED DATE		1998

* TAKES ADVANTAGE OF AUTOMATED, LOW-COST FABRICATION AND ASSEMBLY TECHNIQUES

ITP91-010.7

SPACE SCIENCE TECHNOLOGY PHOTOVOLTAICS

THIN InP SOLAR CELLS PERFORMANCE OBJECTIVE

<u>PERFORMANCE REQUIREMENT</u>	<u>PRESENT SC</u>	<u>DEVELOPMENT GOALS</u>
CELL EFFICIENCY	19.1%	> 20%
CELL THICKNESS (MICROMETER)	380	10
CELL DEGRADATION 10 YEARS GEO	7.5%	<1%
BLANKET SPECIFIC POWER (W/kg)		
BOL	85	425
10 YEARS GEO	79	421
BLANKET SPECIFIC AREAS (W/m ²)		
BOL	173	180
10 YEARS GEO	160	178
APPROXIMATE NEED DATE		1994

ITP91-010.9

SPACE SCIENCE TECHNOLOGY PHOTOVOLTAICS

OTHER DEVELOPMENT EFFORTS

SDIO SUPER ARRAY (SURVIVABLE)

- 15 x CONCENTRATION
- 20% GaAs CELLS
- 15 W/kg
- ≥ 200 W/m²

SPACE STATION FREEDOM ARRAY

- 8 x 8, 8 mil Si CELLS
 - 110 W/m²
 - 40 W/kg
- (NO LEO RADIATION DAMAGE)

ADVANCED TDRSS ARRAY

- Si CELL TECHNOLOGY TBD
- 110 W/m²
- 35 W/kg

AIR FORCE MULTIBANDGAP CELL DEVELOPMENT

- GaAs/Ge
- GaAs/CIS
- AlGaAs/Ge
- FY91 NEW START (~ 1 \$M)
- 30% GOAL
- CELL COST NOT A CONCERN

VARIOUS BLACK PROGRAMS

ITP91-010.10

SPACE ENERGY TECHNOLOGY PHOTOVOLTAIC ENERGY CONVERSION

AUGMENTED PROGRAM

CONCENTRATOR ARRAY TECHNOLOGY

DEMONSTRATE 1 kW CONCENTRATOR ARRAY AT
> 330 W/M, 100 W/kg

THIN FILM EFFICIENCY InP CELLS

DEMONSTRATE THIN (≤ 100 microns) PLANAR InP
CELLS WITH $\geq 20\%$ EFFICIENCY

INITIATE PRE-PILOT PRODUCTION

ITP91-010.13

SPACE ENERGY TECHNOLOGY PHOTOVOLTAIC ENERGY CONVERSION

ROADMAP/SCHEDULE

KEY ACTIVITIES	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000				
<u>R&T BASE</u>														
PHOTOVOLTAIC KEY TECHNOLOGIES RESEARCH														
InP/FOREIGN SUBSTRATES	<table><tr><td>DEVELOP LOW EPD SUBSTRATE</td><td>19% CELL</td><td>RADIATION TEST</td></tr></table>										DEVELOP LOW EPD SUBSTRATE	19% CELL	RADIATION TEST	
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CONCENTRATOR ARRAY	<table><tr><td>DEVELOP 30% CELL & RIGID LENS</td><td>FINAL DESIGN</td><td>COMPLETE FABRICATION</td><td>GROUND TEST</td></tr></table>										DEVELOP 30% CELL & RIGID LENS	FINAL DESIGN	COMPLETE FABRICATION	GROUND TEST
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CIS BLANKET	<table><tr><td>DEVELOP PRECURSORS</td><td>DEMO LOW TEMP. DEPOS</td><td>> 10% CELL</td><td>DEMONSTRATE BLANKET</td></tr></table>										DEVELOP PRECURSORS	DEMO LOW TEMP. DEPOS	> 10% CELL	DEMONSTRATE BLANKET
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20% InP THIN CELL	<table><tr><td>DEMO 20% CELL</td><td>DEMO THIN CELL</td></tr></table>										DEMO 20% CELL	DEMO THIN CELL		
DEMO 20% CELL	DEMO THIN CELL													

**R&T BASE: PHOTOVOLTAIC ENERGY CONVERSION
SUMMARY**

TECHNICAL CHALLENGE:

- o SOLAR ARRAYS WITH EXTENDED LIFE, LIGHTER WEIGHT, SMALLER AREA, REDUCED MISSION COST

APPROACH:

- o ADVANCED CELLS, BLANKETS, ARRAY SYSTEM COMPONENTS
- o INTEGRATED ARRAY SYSTEM HARDWARE

PAYOFF:

- o 10X INCREASE IN ARRAY SPECIFIC POWER
- o RADIATION HARD ARRAYS
- o 3X INCREASE IN POWER DENSITY

RATIONALE FOR AUGMENTATION:

- o ALTERNATE/ENABLING TECHNOLOGY FOR MANY FUTURE MISSIONS
- o AVAILABLE FOR NEAR, MID TERM
- o RESTORES CRITICAL PARTICIPATION BY VENDORS
 - U.S. COMPETITIVE POSITION ERODING

RELATIONSHIP TO FOCUSSED ACTIVITIES AND OTHER PROGRAMS:

- o JOINT ACTIVITIES, MOU's WITH A/F, SDIO, SERI, RAE

TECHNOLOGY CONTRIBUTIONS:

- o OAST1 - BASELINE FOR SSF
- o SILICON CELLS FOR SSF, VIRTUALLY ALL U.S. CIVIL, DOD MISSIONS
- o PIONEERED GaAs CELLS - MANTECH FUNDED BY AIR FORCE

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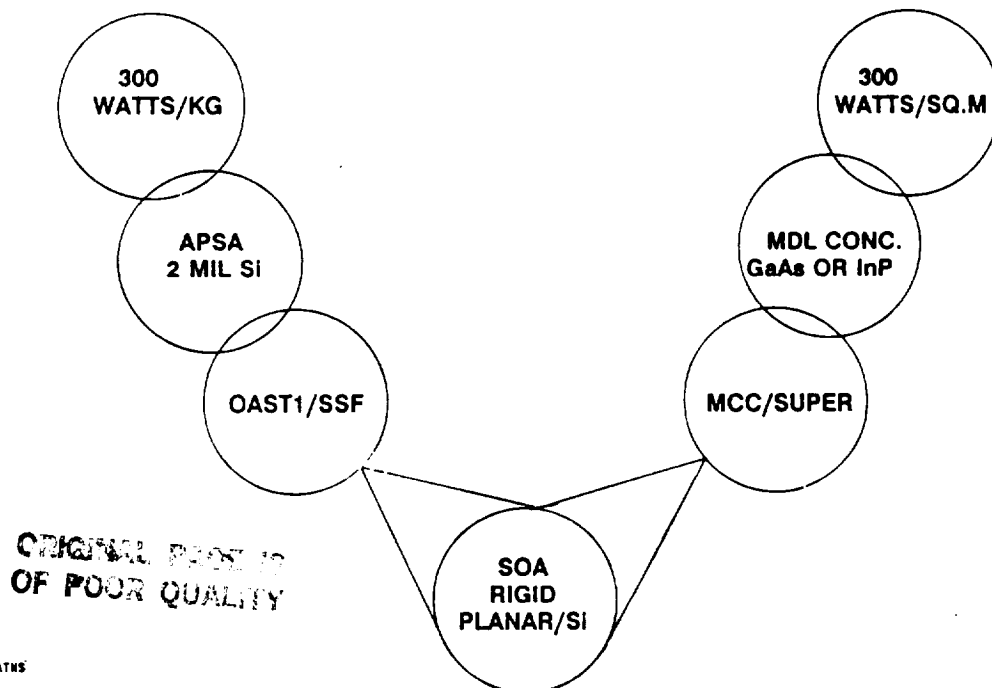
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SPACE ENERGY TECHNOLOGY
SPACE ENERGY CONVERSION

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PHOTOVOLTAIC ENERGY CONVERSION

TWO DISTINCT TECHNOLOGY PATHS



TWO PATHS

SPACE ENERGY TECHNOLOGY SPACE ENERGY CONVERSION

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PHOTOVOLTAIC ENERGY CONVERSION

- o AGENCY PROGRAM HAS TWO MAJOR TECHNOLOGY SUBAREAS:
 - ADVANCED ARRAY TECHNOLOGY
 - ADVANCED SOLAR CELL TECHNOLOGY
- o ADVANCED ARRAY TECHNOLOGY CONSISTS OF ONE MAJOR EFFORT:
 - APSA AND RELATED TECHNOLOGY ISSUES
(LILT EFFECTS, RADIATION DAMAGE, THIN CELLS, ETC)
- o ADVANCED SOLAR CELL TECHNOLOGY CONSISTS OF A "MILLION PIECES"
 - SINGLE CRYSTAL CELLS (InP, GaAs, AlGaAs, InGaAs, MBG's, ETC); THIN FILM CELLS (CIS, a-Si) FLEXIBLE SUBSTRATES, ALTERNATE SINGLE CRYSTAL SUBSTRATES; CONCENTRATOR CELLS & OPTICS; THERMAL CYCLING TESTS; FLIGHT TESTS (UOSAT, PASP-PLUS, APEX); CELL MEASUREMENT AND CALIBRATION, ETC, ETC

PROGRATS

SPACE ENERGY TECHNOLOGY SPACE ENERGY CONVERSION

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PHOTOVOLTAIC ENERGY CONVERSION

- o EVEN THE SOA HAS
 - FEW ARRAY DESIGNS
(COSTLY, STICK WITH WHAT'S FLOWN...)
 - MANY SILICON SOLAR CELL TYPES
10 OHM-CM, 2 OHM CM, BSF, BSR, BSFR, TEXTURED, 2X4CM, 4X2CM,
2X6CM, 6X6CM, 8X8CM, BACKSIDE GRIDS, 2MIL, 8MIL, 12MIL ETC, ETC

WHY?

- o BECAUSE MISSIONS FLY IN DIFFERENT ENVIRONMENTS WITH DIFFERENT PERFORMANCE REQUIREMENTS
 - NO ONE SI CELL, EVEN ON THE SAME ARRAY DESIGN, GIVES OPTIMUM PERFORMANCE FOR ALL MISSIONS
- o A "CATALOG" OF ADVANCED SOLAR CELLS IS SIMILARLY NEEDED TO OPTIMIZE FUTURE MISSIONS
 - ADVANCED "OPTIMUM" CELLS ARE MADE FROM DIFFERENT MATERIALS, DIFFERENT CONFIGURATIONS

REASON FOR ALL THIS? THE USER COMMUNITY

PROPERT1

SPACE ENERGY TECHNOLOGY
SPACE ENERGY CONVERSION

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PHOTOVOLTAIC ENERGY CONVERSION

THE BOTTOM LINE:

- o BASE R&T FUNDING AT LEAST ONE-THIRD LESS (REAL DOLLARS) THAN DECADE AGO

CAUSE:

- o CONSTRAINED POWER R&T BUDGET W/LARGE EFFORTS TO DEVELOP ALTERNATE TECHNOLOGIES
 - GROWTH SPACE STATION/SOLAR DYNAMICS
 - LUNAR BASE/SP-100
 - NEP NEXT?

EFFECT:

- o LARGE INVESTMENTS IN ALTERNATE SYSTEMS FOR FAR TERM (BEYOND 2000) HAVE ERODED AGENCY'S ABILITY TO HAVE IMPACT ON NEAR AND MID TERM MISSIONS

CONSEQUENCE:

- o REDUCED FUNDING PUSHES NEAR AND MID TERM PV TECHNOLOGY TO FAR TERM
 - VENDORS DROP OUT
 - USER COMMUNITY CAN'T WAIT
 - MISSION CAPABILITIES COMPROMISED

01/20/00

INTEGRATED TECHNOLOGY PLAN
FOR THE CIVIL SPACE PROGRAM

**CHEMICAL ENERGY CONVERSION AND STORAGE
TECHNOLOGY PROJECT SUMMARY**

SPACE ENERGY CONVERSION
PROGRAM AREA OF THE
R&T BASE PROGRAM

June 26, 1991

P. Bankston and M. Warshay

SPACE ENERGY CONVERSION BASE R&T

CHEMICAL ENERGY CONVERSION & STORAGE

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PROGRAM OVERVIEW

OBJECTIVES

- **Programmatic**
Develop and Demonstrate Advanced
Rechargeable Battery and Fuel Cell
Technologies for Space Applications
- **Technical**

Specific Energy	100-200 Wh/Kg
Energy Density	150-300 Wh/l
Operational Life	10 years

SCHEDULE

- 1993 5 Ah Engineering Model LiTiS₂ Cell
- 1994 Deliver Bipolar Flight Battery
- 1995 Demonstrate 1000 Cycles at 50% DOD and
100 Wh/Kg For LiTiS₂ Cells
Complete 100 Wh/Kg Nickel-Hydrogen
Battery
- 1996 Bi-functional Catalyst Technology
Developed
- 1997 Design for 150 Wh/Kg Battery

RESOURCES(\$M)

BASELINE

STRATEGIC

• 1991	1.8	—
• 1992	2.0	—
• 1993	2.1	2.8
• 1994	2.2	3.4
• 1995	2.3	3.9
• 1996	2.4	4.4
• 1997	2.5	5.0

PARTICIPANTS

- Lewis Research Center
Responsibility includes advanced batteries
and fuel cells
- Jet Propulsion Laboratory
Responsibility includes advanced batteries

SPACE ENERGY CONVERSION BASE R&T

= OAET CHEMICAL ENERGY CONVERSION & STORAGE

TECHNOLOGY NEEDS

- **THE CHEMICAL ENERGY CONVERSION AND STORAGE TECHNOLOGY PROGRAM WILL SUPPORT EMERGING EARTH ORBITAL, PLANETARY AND SCIENCE MISSIONS DEMANDING HIGH SPECIFIC ENERGY (3X STATE OF THE ART) AND LONG-LIFE RECHARGEABLE BATTERIES, INCLUDING**
 - **PLANETARY SPACECRAFT**
 - **RECHARGEABLE LITHIUM, NICKEL-HYDROGEN SYSTEMS OR ADVANCED CONCEPTS**
 - **SURFACE EXPLORERS/ROVERS**
 - **RECHARGEABLE LI, NIH₂, FUEL CELLS OR ADVANCED CONCEPTS**
 - **LUNAR/MARS SURFACE POWER**
 - **REGENERATIVE FUEL CELLS**
 - **PROBES AND PENETRATORS**
 - **RECHARGEABLE LITHIUM**
 - **ALL NEAR-EARTH MISSIONS (ATDRSS/EOS/SATCOMS/SSF/SHUTTLE/EVAs)**
 - **MARS AND VENUS MISSION POWER**
 - **LICO₂ SYSTEM**
 - **EMA's FOR SHUTTLE**
 - **BI-POLAR NIH₂ WITH ELECTROCHEMICAL CAPACITORS**

SPACE ENERGY CONVERSION BASE R&T

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TECHNOLOGY CHALLENGES

- **REDUCE BATTERY WEIGHT (2-3 TIMES LESS THAN NI-Cd)**
- **REDUCE BATTERY VOLUME (2-3 TIMES)**
- **INCREASE OPERATIONAL LIFE (10 YEARS)**
- **DEVELOP A BATTERY FOR HIGH VOLTAGE, HIGH POWER, AND PULSE APPLICATIONS**
- **EXTEND ACTIVE STORAGE/CHARGE RETENTION (5 YEARS)**
- **STABLE, HIGH PERFORMANCE FUEL CELL CATALYSTS**
- **IDENTIFY ADVANCED CONCEPTS CAPABLE OF FURTHER ENERGY STORAGE IMPROVEMENTS BY FACTORS OF 3-5 BEYOND SOA**

CHEMICAL ENERGY CONVERSION & STORAGE

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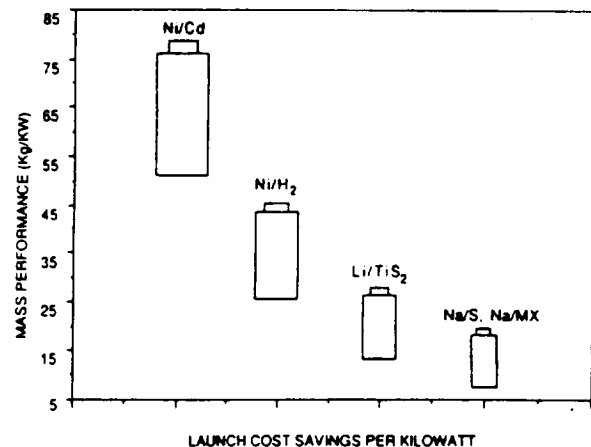
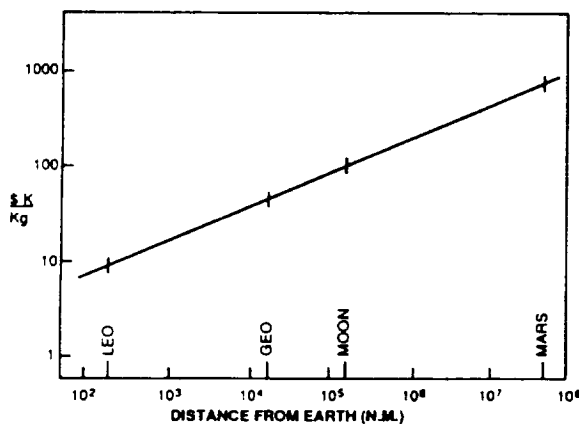
TECHNOLOGY BENEFITS

- MASS REDUCTION ENABLES SIGNIFICANT LAUNCH COST SAVINGS PER KILOWATT OR WATT-HOUR ENERGY STORED; AND INCREASE IN PAYLOAD CAPABILITY
- 2-3 TIMES SAVING IN ENERGY STORAGE VOLUME ENABLES REDUCTIONS IN SYSTEM ENVELOPE
- INCREASE OF OPERATION LIFE TO 10 YEARS OR MORE ENABLES PLANETARY MISSION APPLICATIONS
- HIGH POWER, HIGH VOLTAGE BATTERY DEVELOPMENT WOULD PROVIDE PRIMARY POWER OPTION FOR LARGE LUNAR/PLANETARY ROVERS
- STABLE, HIGH PERFORMANCE CATALYSTS WOULD ENABLE REGENERATIVE FUEL CELL UTILIZATION FOR WIDE RANGE OF LUNAR AND PLANETARY SURFACE POWER SYSTEMS

CHEMICAL ENERGY CONVERSION & STORAGE

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MASS COST ADVANTAGE



CHEMICAL ENERGY CONVERSION & STORAGE

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STATE OF THE ART ASSESSMENT

- SOA RECHARGEABLE BATTERIES ARE ACCEPTABLE, BUT POSSESS LOW SPECIFIC ENERGY (30 Wh/Kg, Ni-Cd; 55 WH/Kg, NiH₂) AND ENERGY DENSITY.
- 10 YEAR OPERATIONAL LIFE WHILE CYCLING DEMONSTRATED FOR SOME; MANY YEARS ON STAND (CRUISE) GENERALLY NOT DEMONSTRATED
- SOA RECHARGEABLE BATTERIES TYPICALLY HAVE POOR CHARGE RETENTION CHARACTERISTICS
- NO HIGH VOLTAGE, HIGH POWER SPACE BATTERY YET DEVELOPED
- STABLE, HIGH PERFORMANCE CATALYSTS ESSENTIAL TO REGENERATIVE FUEL CELL UTILIZATION IN SPACE

CHEMICAL ENERGY CONVERSION & STORAGE

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ADVANCED RECHARGEABLE BATTERY TECHNOLOGY PERFORMANCE OBJECTIVES (CELL LEVEL)

PERFORMANCE CHARACTERISTIC	SOA BATTERIES		ADVANCED BATTERIES			
	NiCd	NiH ₂	IPV NiH ₂	BP* NiH ₂	LiTiS ₂	Na-S Na-MX
SPECIFIC ENERGY (Wh/Kg)	30	55	100	80	100	140-200
ENERGY DENSITY (Wh/l)	80	60	80	120	250	300
MASS PERFORMANCE (Kg/Kw)	65	35	20	25	20	14-10
CAPACITY (Ah)	5-50	30-250	30-300	30-300	5-30	100
OPERATING TEMPERATURE (°C)	-10-35	-10-35	-10-35	-10-35	0-30	350-300
CYCLE LIFE (# Cycles @ 70% DOD)	1000	40,000	40,000	40,000	1000	2000
MINIMUM LIFE TIME (Years)	10	10	10	10	5-10	5-10

* On a battery (10 cell pack) level.

SPACE ENERGY CONVERSION BASE R&T

CHEMICAL ENERGY CONVERSION & STORAGE

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RECENT MAJOR ACCOMPLISHMENTS

- IPV NIH₂
 - 40,000 LEO CYCLES AT 80% DOD IN BOILERPLATE CELLS
 - LIGHTWEIGHT COMPONENT TECHNOLOGY DEMONSTRATED FOR 5800 CYCLES ON SUBSCALE LEVEL
 - 90% NI ELECTRODE SUBSTRATE POROSITY ACHIEVED (vs. 83% SOA)
- BIPOLAR NIH₂
 - OVER 10,000 CYCLES ACHIEVED IN ON-GOING TESTS
- LI-TIS₂
 - 700 CYCLES ACHIEVED AT 50% DOD IN 1 Ah CELLS
- ADVANCED RECHARGEABLE BATTERY CONCEPTS
 - CONFIRMED CYCLEABILITY OF NaNiCl₂ CELL; SELECTED FOR TECHNOLOGY DEVELOPMENT

SPACE ENERGY CONVERSION BASE R&T

CHEMICAL ENERGY CONVERSION & STORAGE

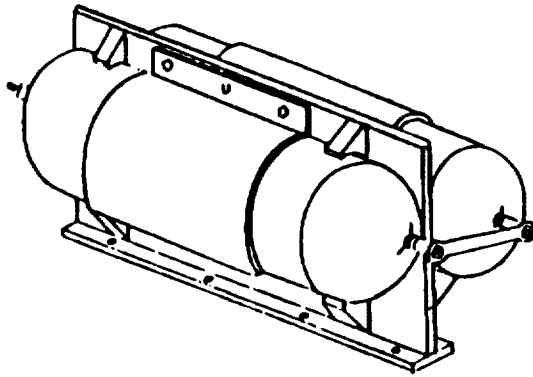
LeRC

CURRENT PROGRAM

- DEVELOP GEO NICKEL HYDROGEN (NI/H₂) BATTERIES WITH INCREASED ENERGY DENSITY (100 Whr/Kg) AND RELIABILITY BY 1995
 - INTERIM 60 Whr/Kg (80% DOD) BY 1993
 - LIGHTWEIGHT COMPONENT TECHNOLOGY
 - HIGH PERFORMANCE NICKEL ELECTRODE DEVELOPMENT
- DEVELOP BIPOLAR NI/H₂ BATTERY FOR HIGH VOLTAGE, HIGH POWER, HIGH CURRENT, AND PULSE APPLICATIONS BY 1994
 - IN-HOUSE AND CONTRACT CYCLE LIFE TESTING
 - FABRICATE AND TEST ADVANCED BOILERPLATE BATTERY IN 1992
- DEVELOP ADVANCED SODIUM SULFUR (Na/S) BATTERIES AS VIABLE NASA FLIGHT SYSTEMS
 - MANAGEMENT OF \$5M IN-STEP FLIGHT EXPERIMENT
 - INITIATE TECHNOLOGY DEVELOPMENT IN 1993
- DEVELOP STABLE, HIGH PERFORMANCE FUEL CELL CATALYSTS
 - COMPLETE EVALUATION OF LeRC LONG-LIFE CATALYSTS IN SOA PEM FUEL CELL IN 1993
 - CATALYST/SUPPORT TECHNOLOGY FOR REGENERATIVE FUEL CELL SYSTEM
 - BI-FUNCTIONAL CATALYST TECHNOLOGY



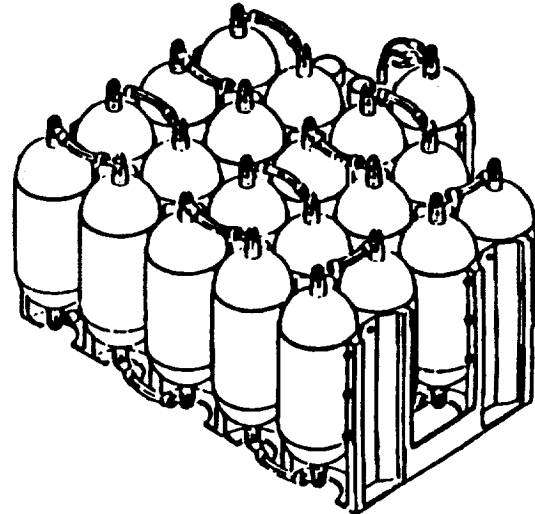
SIZE AND VOLUME COMPARISON OF 1.4 kWhr BIPOLAR AND IPV NICKEL HYDROGEN SYSTEMS



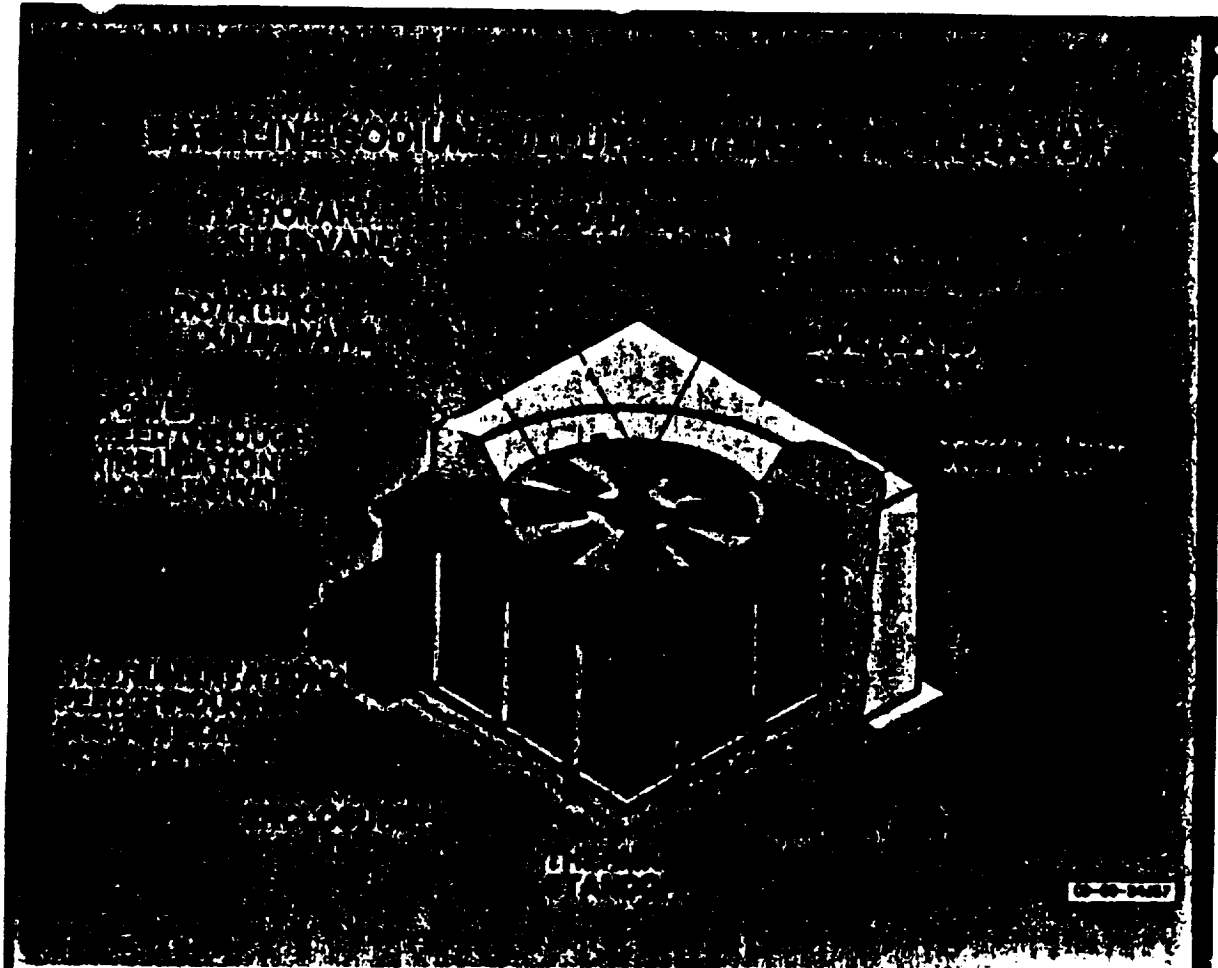
BIPOLAR BATTERY
2 X 100 CELLS (~133 VOLTS)

BIPOLAR DESIGN REPRESENTS
~10% VOLUME REDUCTION
COMPARED TO IPV

IPV BATTERY
21 CELLS (~28 VOLTS)



ORIGINAL PAGE IS
OF POOR QUALITY



CHEMICAL ENERGY CONVERSION & STORAGE

= LeRC

- IPV NICKEL HYDROGEN
- SODIUM SULFUR
- FUEL CELLS
- ELECTROCHEMICAL CAPACITORS

- DEVELOP COMMERCIAL MANUFACTURING CAPABILITY
- ACCELERATED PROGRAM
 - TIMELY
 - BETTER PHASING
 - TIMELY PRODUCTION, MANUFACTURING CAPABILITY
- CATALYST LIFE TEST, AND HALF CELL TEST
- ENHANCE IN-HOUSE FUEL CELL TESTING CAPABILITY
- INITIATE ELECTROCHEMICAL CAPACITOR DEVELOPMENT PROGRAM

CHEMICAL ENERGY CONVERSION & STORAGE

= LeRC

KEY ACTIVITIES	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
NICKEL HYDROGEN TECHNOLOGY										
GEO LIGHTWEIGHT IPV HIGH SP, ENERGY		COMPONENT DEV	60 WH/Kg FLIGHT CELL VERIFICATION		100 WH/Kg		MOVE TO FOCUSED PROGRAM			
						MANUFACT. CAPABILITY IN PLACE				
BPOLAR		BOILER PLATE TESTING	POST TEST ANALYSIS	DELIVERY			MOVE TO FOCUSED PROGRAM			
				FLIGHT BATTERY DESIGN/BUILD		MISSION SUPPORT TESTING				
SODIUM SULFUR			CELL TECHNOLOGY SYSTEMS ANALYSIS DESIGN VERIFICATION			LAUNCH		ADVANCED DESIGN		
							LAUNCH			
FUEL CELL CATALYSTS		TESTING								
				STACK VALIDATION						
ADVANCED CONCEPTS				SINGLE CELL STACK		MULTI CELL STACK				
ELECTROCHEMICAL CAPACITORS				STACK DEVELOPMENT						
					STACK FABRICATION					
LITHIUM CARBON DIOXIDE				TECHNOLOGY DEVELOPMENT						

C-2

JPL CHEMICAL ENERGY CONVERSION & STORAGE

CURRENT PROGRAM

- DEMO FEASIBILITY OF AMBIENT TEMPERATURE Li-TiS₂ CELL TECHNOLOGY (100 Wh/Kg) BY 1995
 - IDENTIFY STABLE ELECTROLYTES
 - EVALUATE ALTERNATE LI ANODE MATERIALS
 - DEVELOP OVERCHARGE CONCEPTS
 - DEFINE DESIGN REQUIREMENTS
 - DEVELOP 5 Ah CELLS
 - ASSESS SAFETY
- DEVELOP ADVANCED BATTERY SYSTEMS CAPABLE OF >150 Wh/Kg
 - SODIUM/METAL HALIDES
 - LITHIUM/POLYMER ELECTROLYTE/INSERTION CATHODES
 - SELECT CANDIDATE SYSTEM
 - DEMONSTRATE CYCLE LIFE
 - DEVELOP ENGINEERING MODEL CELL
 - DEMONSTRATE TECHNOLOGY

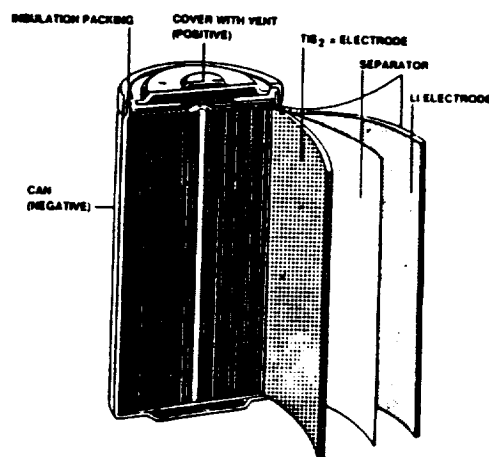
JPL RECHARGEABLE LITHIUM CELL PROGRAM

SCALE UP OF Li-TiS₂ CELL TECHNOLOGY

CELL DESIGN

<u>COMPONENT</u>	<u>150 mAh CELL</u>	<u>1 Ah CELL</u>
LI ANODE	1.5 Ah (1' x 4.5" x 0.02")	6 Ah (1.6" x 10" x 0.02")
TiS ₂ CATHODE	150 mAh (1' x 2" x 0.02")	1 Ah (1.6" x 8.5" x 0.02")
ELECTROLYTE	EC/2-MeTHF, 4 c.c.	EC/2-MeTHF, 6 c.c.
SEPARATOR	CELGARD 2400	CELGARD 2400
SEAL	GLASS TO METAL	GLASS TO METAL
CAN	S.S. 304L	S.S. 304L

CELL STRUCTURE



SPACE ENERGY CONVERSION BASE R&T

CHEMICAL ENERGY CONVERSION & STORAGE

JPL

STRATEGIC PROGRAM

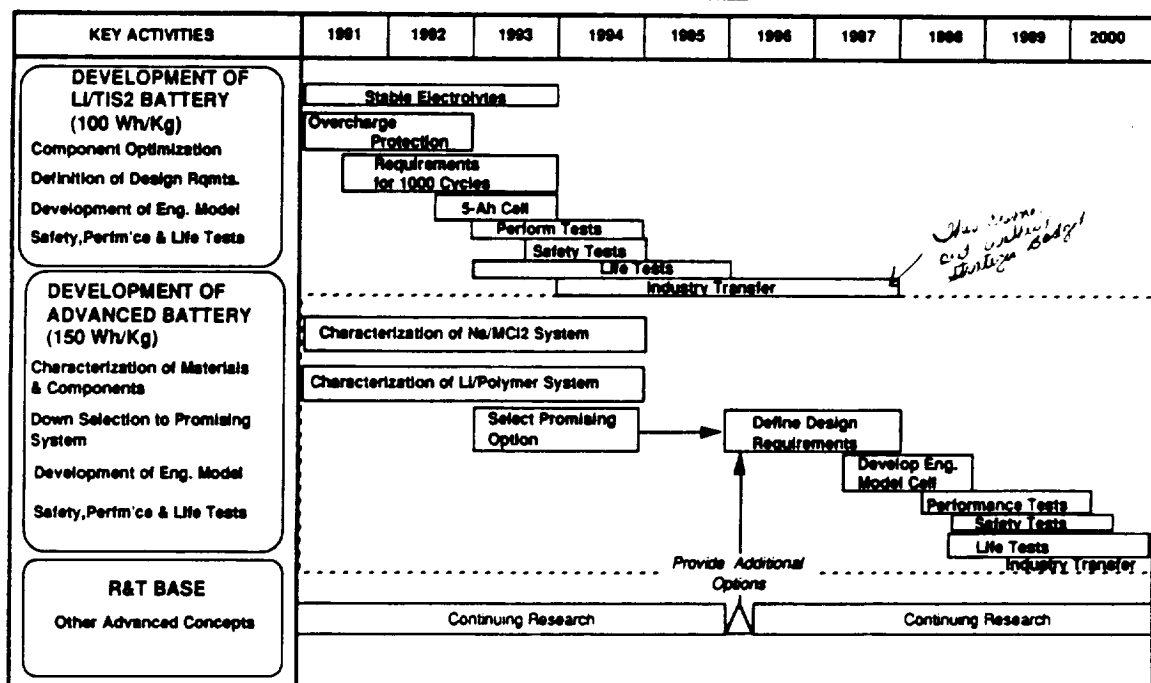
- DEVELOP AND TRANSFER TECHNOLOGY TO INDUSTRY FOR 30 Ah, 30 V, LI-TIS₂ CELL BY 1996
 - ACTIVITIES
 - ISSUE CONTRACT TO INDUSTRY
 - DEVELOP PROTOTYPE 30 Ah CELL
 - COMPLETE SAFETY, LIFE AND PERFORMANCE TESTS
- ACCELERATE 150 Whr/Kg CELL DEVELOPMENT

SPACE ENERGY CONVERSION BASE R&T

CHEMICAL ENERGY CONVERSION & STORAGE

JPL

ROADMAP/SCHEDULE



SPACE ENERGY CONVERSION BASE R&T

OAET **CHEMICAL ENERGY CONVERSION & STORAGE**

RESOURCE REQUIREMENTS

<u>FY</u>	<u>BASELINE FUNDING (\$M)</u>	<u>STRATEGIC FUNDING (\$M)</u>
91	1.8	--
92	2.0	--
93	2.1	2.8
94	2.2	3.4
95	2.3	3.9
96	2.4	4.4
97	2.5	5.0

SPACE ENERGY CONVERSION BASE R&T

OAET **CHEMICAL ENERGY CONVERSION & STORAGE**

RELATIONSHIP TO FOCUSSED PROGRAM

LeRC

MANAGE:

- NASA AEROSPACE FLIGHT BATTERY SYSTEMS PROGRAM - CODE Q
- EXPLORATION REGENERATIVE FUEL CELL (RFC) TECHNOLOGY DEVELOPMENT PROGRAM (SOLAR SURFACE POWER)

SUPPORT:

- EXPLORATION SOLAR SURFACE POWER PROGRAM
- SPACE STATION, HST, EOS, AND ADVANCED TDRSS NICKEL HYDROGEN BATTERY PROGRAMS

JPL

- SUPPORT NASA AEROSPACE FLIGHT BATTERY SYSTEMS PROGRAM - CODE Q
- R&T BASE TAKES LI-TIS2 BATTERY DEVELOPMENT TO "GENERIC" CELL COMPONENT AND DESIGN DEMONSTRATION
- SPACECRAFT PLATFORMS PROGRAM ADDRESSES LI-TIS2 CELL AND BATTERY DEVELOPMENT WITH APPLICATIONS FOCUS
- ADVANCED RECHARGEABLE BATTERY CONCEPTS NOT ADDRESSED IN FOCUSED PROGRAM

CHEMICAL ENERGY CONVERSION & STORAGE

OAET

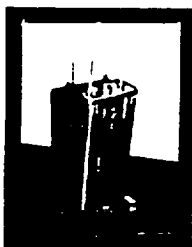
RELATED TECHNOLOGY AREAS/EFFORTS

- PRIMARY LITHIUM BATTERY DEVELOPMENT FOR CENTAUR - AIR FORCE PROGRAM MANAGED BY JPL
- LABCOM, NSWC, AND AIR FORCE ARE DEVELOPING (AMBIENT) RECHARGEABLE LI BATTERIES FOR DEFENSE APPLICATIONS - (USUALLY FOR LIMITED CYCLE LIFE - 50 CYCLES)
- DOE LABS ARE WORKING PROGRAMS TO DEVELOP LI-POLYMER AND SODIUM METAL CHLORIDE BATTERIES FOR TRANSPORTATION; ALSO Ni-METAL HYDRIDE FOR DEFENSE SPACE (JPL INVOLVED)
- AIR FORCE IS DEVELOPING Na-S BATTERY FOR DEFENSE SPACE APPLICATIONS
- SSF, HST, EOS, AND ADVANCED TDRSS Ni-H₂ BATTERY PROGRAMS SUPPORTED BY LeRC
- EMA APPLICATIONS STUDY UTILIZING BIPOLAR Ni-H₂ BATTERY
- DARPA UNMANNED UNDERSEA VEHICLE BATTERY POWER PROGRAM MANAGED BY LeRC
- DARPA UNMANNED UNDERSEA VEHICLE FUEL CELL POWER PROGRAM MANAGED BY LeRC
- LeRC COORDINATING WITH DOE PEM FUEL CELL PROGRAM (PASSENGER CAR APPLICATION)

JPL

CENTAUR Li-SOCl₂ BATTERY

**ALLIANT
VERSION**



3.4 V - 250 AH CELL

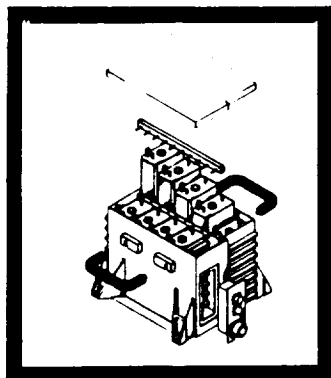
FEATURES

- WEIGHT: 75 lb, 34 kg
(1/2 OF EXISTING SILVER-ZINC BATTERY)
- LOW TEMPERATURE LIFE: 6 yrs @ 0°F
- AMBIENT TEMPERATURE LIFE: 1 yr @ 40-90°F
(10 TIMES EXISTING SILVER-ZINC BATTERY)
- CURRENT:
 - CONTINUOUS > 40 A
 - SHORT TERM > 75 A

**YARDNEY
VERSION**



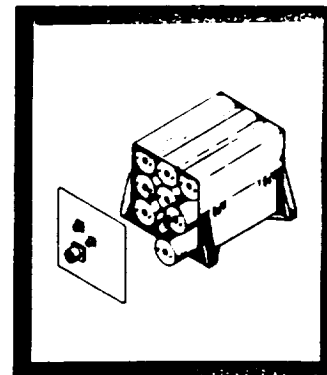
3.4 V - 250 AH CELL



28 V - 250 AH BATTERY

STATUS

QUALIFICATION
OF DESIGN
AND MCD 9/91



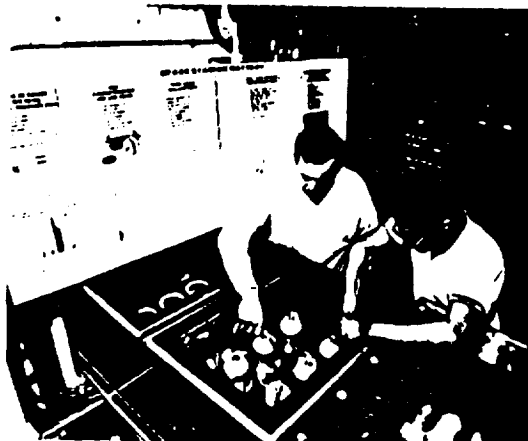
28 V - 250 AH BATTERY



POWER TECHNOLOGY DIVISION



IPV NICKEL HYDROGEN CELL TESTING SPACE STATION FREEDOM SUPPORT



Space Station Freedom Ni-H₂ Cells

- LEO life tests 40% DOD
- 39 Flightweight cells on test
- 50 Ah and 65 Ah capacity
- 3 Commercial vendors
- 10 °C and -5 °C temperatures
- 35% Depth-of-discharge
- 26% and 31% KOH comparison
- Cell design variations

CD-90-00995

SPACE ENERGY CONVERSION BASE R&T

CHEMICAL ENERGY CONVERSION & STORAGE

OAET

SUMMARY

- **TECHNICAL CHALLENGE:** INCREASE PAYLOAD BY REDUCING BATTERY SYSTEM WEIGHT (2X-4X) AND VOLUME WITH OPERATIONAL LIFE BEYOND 10 YEARS. ALSO, PROVIDE HIGH VOLTAGE, PULSE POWER CAPABILITY.
- **APPROACH:** DEVELOP ADVANCED NICKEL-HYDROGEN BATTERY TECHNOLOGY FOR (2X-3X) STORAGE IMPROVEMENT FOR LARGER SYSTEMS (>1kW); AND Li-TiS₂ FOR 2X-3X IMPROVEMENT IN SMALLER (<1kW) SYSTEMS. DEVELOP RECHARGEABLE SODIUM SYSTEMS FOR 3X-5X IMPROVEMENTS IN LONG TERM. CONDUCT FUEL CELL CATALYST RESEARCH AND DEVELOP ADVANCED CONCEPTS.
- **PAYOFF:**
 - MASS AND VOLUME REDUCTION ENABLES SIGNIFICANT LAUNCH COST SAVINGS PER KILOWATT OR WATT-HOUR ENERGY STORED
 - INCREASE OF OPERATIONAL LIFE TO 10 YEARS OR MORE ENABLES PLANETARY MISSION APPLICATIONS
 - HIGH POWER, HIGH VOLTAGE BATTERY DEVELOPMENT WOULD PROVIDE PRIMARY POWER OPTION FOR LARGE LUNAR/PLANETARY ROVERS
 - STABLE, HIGH PERFORMANCE CATALYSTS WOULD ENABLE REGENERATIVE FUEL CELL UTILIZATION FOR WIDE RANGE OF LUNAR AND PLANETARY SURFACE POWER SYSTEMS
- **RATIONALE FOR AUGMENTATION:**
 - ACCELERATE TECHNOLOGY DEVELOPMENT FOR TIMELY TRANSFER TO USER (e.g., Na-S IN PHASE WITH FLIGHT EXPERIMENT, RFC CATALYST FOR EXPLORATION, LiTiS₂ FOR PLATFORMS)
 - INITIATE NEW TECHNOLOGY DEVELOPMENT (e.g., ELECTROCHEMICAL CAPACITOR, POLYMER BATTERY)
- **RELATIONSHIP TO FOCUSED ACTIVITIES AND OTHER PROGRAMS:**
 - PROGRAM DESIGNED TO SUPPORT VIRTUALLY ALL FOCUSED TECHNOLOGY PROGRAMS
 - LARC AND JPL PROVIDE PROGRAM MANAGEMENT, TRANSFER TECHNOLOGY, AND COORDINATE WITH OTHER NASA CODES, DOD, AND DOE
- **TECHNOLOGY CONTRIBUTIONS:**
 - LEO IPV NICKEL HYDROGEN BATTERY TECHNOLOGY TRANSFERRED TO NASA (HST AND SSF), MILITARY AND INDUSTRY APPLICATIONS
 - LITHIUM THIONYLCHLORIDE (PRIMARY) BATTERY TECHNOLOGY TRANSFERRED TO AIR FORCE FOR CENTAUR



SPACE ENERGY CONVERSION R&T

SPACE ENERGY CONVERSION R&T PROGRAM

506-41

THERMAL ENERGY CONVERSION SUBELEMENT

506-41-31

PRESENTED AT THE ITP EXTERNAL REVIEW

June 26, 1991

Power Technology Division of the Aerospace Technology Directorate
NASA Lewis Research Center

Cleveland, Ohio 44135

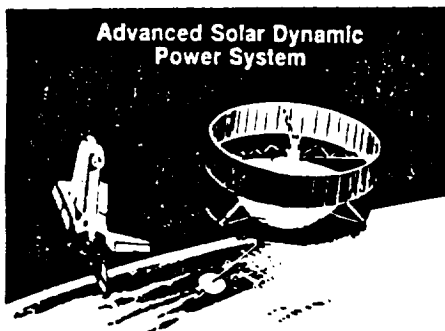
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SPACE ENERGY CONVERSION R&T

THERMAL ENERGY CONVERSION

WHAT WE WILL DISCUSS



- PROGRAM OVERVIEW
- MISSIONS AND BENEFITS
- CURRENT PROGRAM DESCRIPTION
- STRATEGIC PROGRAM DESCRIPTION
- ROADMAP/SCHEDULE/RESOURCES
- RELATED DEVELOPMENT EFFORTS
- SUMMARY

ITP JEC91-001.2

SPACE ENERGY CONVERSION BASE R&T THERMAL ENERGY CONVERSION

OAET

THERMAL ENERGY CONVERSION

OBJECTIVES

• Programmatic

Develop and Demonstrate High-Efficiency Solar Dynamic, Thermoelectric, Brayton/Stirling, and Alkali Metal Thermoelectric Conversion (AMTEC) Technologies

• Technical

System Efficiency - > 20%

Specific Power - 12 W/kg (TE)
16 - 20 W/kg (SD)
15 W/kg (AMTEC)

SCHEDULE

- 1993 Demonstrate Technical Feasibility of Solar Dynamic Heat Receiver Technologies
- 1994 15% Efficiency, 3000-Hour AMTEC
Complete Critical Technology Experiments to Utilize Lunar in-situ Materials for TES
- 1995 Identify Advanced Thermoelectric Material with $Z = 1.4 \text{ E-03/K}$
- 1996 Complete Critical Technology Experiment for Advanced Sensible Heat Receiver
- 1997 Prototype Static Conversion Module Design

RESOURCES (\$M)	CURRENT	STRATEGIC
• 1991	1.7	--
• 1992	1.4	--
• 1993	1.5	1.8
• 1994	1.6	2.1
• 1995	1.7	2.4
• 1996	1.8	2.7
• 1997	1.9	3.0

PARTICIPANTS

- Lewis Research Center
Responsibility includes advanced solar dynamic systems, Brayton/Stirling technologies
- Jet Propulsion Laboratory
Responsibility includes advanced thermoelectrics and AMTEC

ITP JEC91-001.3



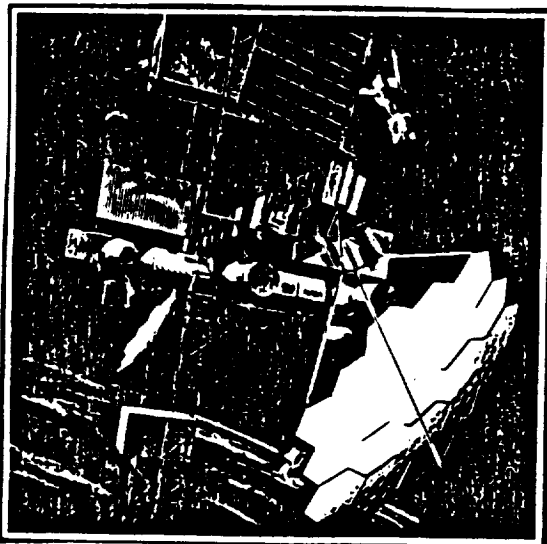
SPACE ENERGY CONVERSION R&T

THERMAL ENERGY CONVERSION

MISSION & BENEFITS

• EARTH ORBITING PLATFORMS •

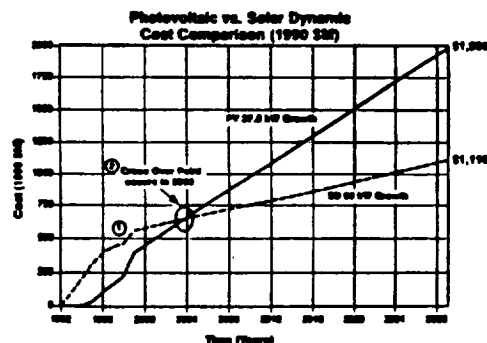
SPACE STATION FREEDOM



QUALITATIVE BENEFITS

- MORE FLEXIBILITY
- LONG LIFE COMPONENTS
- LESS DRAG
- LOWER MASS
- LOWER RECURRING COSTS
- LESS AGGREGATE EVA

QUANTITATIVE BENEFITS



Notes: 1. Step change between 1980 and 1990 is due to initial launch cost.
2. Current Solar Dynamic Station in 1990 is 10 W/kg PV and 20 W/kg SD power modules, in a balanced station configuration. Once our model starts prior to year 2000 for constant growth power levels.

EC91-001.4

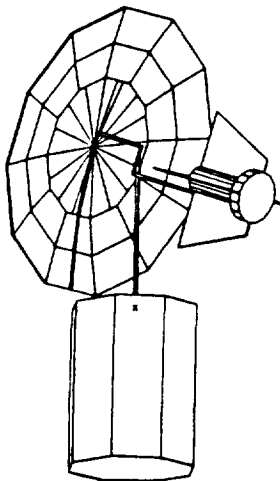


SPACE ENERGY CONVERSION R&T

THERMAL ENERGY CONVERSION

MISSION & BENEFITS
- EARTH ORBITING PLATFORMS -

SMALL SATELLITES
COMMUNICATIONS, EARTH OBSERVING



QUALITATIVE BENEFITS

- LONGER MISSION LIFE
 - LOWER AMORTIZED COSTS
- LESS SUSCEPTIBILITY TO RADIATION EFFECTS
 - OPERATIONAL FLEXIBILITY

ITP JEC91-001.5

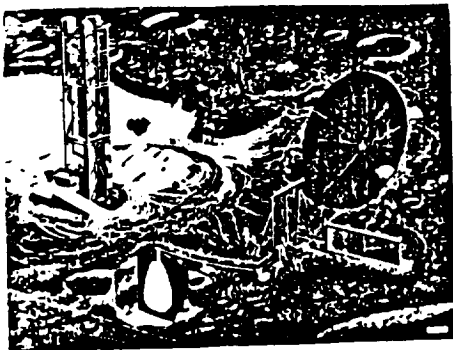


SPACE ENERGY CONVERSION R&T

THERMAL ENERGY CONVERSION

MISSION & BENEFITS
- SURFACE POWER -

LUNAR BASE SD POWER SYSTEM &
OXYGEN PROCESS PLANT

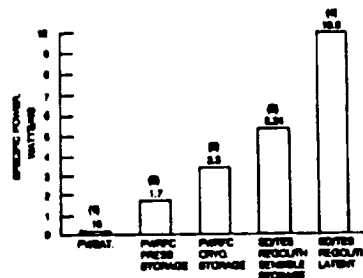


QUALITATIVE BENEFITS

- PROVIDES PROCESS HEAT PLUS ELECTRICAL POWER
- USES IN-SITU MATERIALS FOR TES
- LONG LIFE COMPONENTS

QUANTITATIVE BENEFITS

COMPARISON OF ALTERNATE SOLAR
POWER SYSTEMS FOR LUNAR BASE



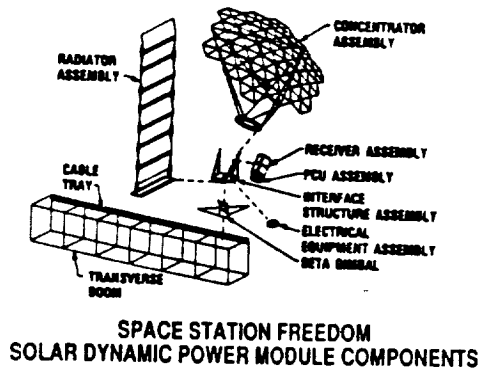
(A) REFERENCE (10)
(B) REFERENCE (11)
(C) PRIVATE COMMUNICATION & TELEVISION, SCIENCE AEROSPACE
AND ELECTRONICS

ITP JEC91-001.5



SPACE ENERGY CONVERSION R&T

THERMAL ENERGY CONVERSION



CURRENT PROGRAM DESCRIPTION *(Subsection 1)*

- IDENTIFY/ANALYZE INNOVATIVE COMPONENT/SYSTEM CONCEPTS
- DEVELOP HIGH EFFICIENCY, LOW MASS AUTO-DEPLOYABLE ADVANCED CONCENTRATOR TECHNOLOGIES
- IDENTIFY AND DEVELOP ADVANCED HEAT RECEIVER TECHNOLOGIES
- IDENTIFY AND DEVELOP THERMAL ENERGY STORAGE CONCEPTS FOR THE LUNAR SURFACE USING LUNAR REGOLITH

ITP-JEC91-00.7



SPACE ENERGY CONVERSION R&T

THERMAL ENERGY CONVERSION

SOLAR DYNAMIC TECHNOLOGY PERFORMANCE GOALS

PERFORMANCE REQUIREMENT	CURRENT SOA	ADVANCED SOLAR DYNAMICS (ASD)
<u>ORBITAL SYSTEMS</u>		
• SPECIFIC POWER	5 - 8 W/kg	16 - 20 W/kg
• CONCENTRATOR		
- MASS	4 kg/sq. m.	1-2 kg/sq. m.
- ACCURACY	4 MILLIRADIANS	1 MILLIRADIAN
• RECEIVER		
- MASS	50 kg/kW	25 kg/kW
<u>LUNAR SYSTEMS</u>		
• SPECIFIC POWER	1 - 3 W/kg	5 - 10 W/kg



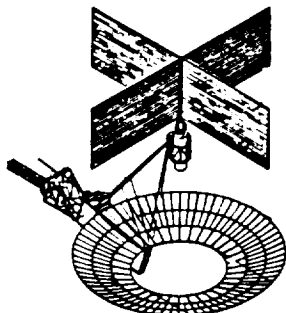
SPACE ENERGY CONVERSION R&T

THERMAL ENERGY CONVERSION

DESIGN & ANALYSES

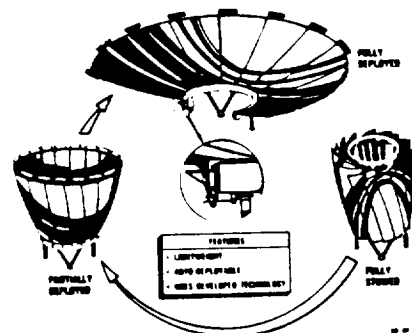
OBJECTIVES

- IDENTIFY INNOVATIVE COMPONENT & SYSTEM CONCEPTS
- IDENTIFY CRITICAL TECHNOLOGIES
- PROVIDE SPACECRAFT AND SUBSYSTEM INTERFACE REQUIREMENTS



ACUREX CORP. SOLAR DYNAMIC POWER SYSTEM CONCEPT

NASA/CSU-AMC PROTOTYPE AUTO-DEPLOYABLE CONCENTRATOR



MILESTONES

- 1992 COMPLETE CONCEPTUAL DESIGN OF 5 kW HYBRID (PV/SD) SPACECRAFT
- 1993 DEFINE SUBSYSTEM REQUIREMENTS FOR ADVANCED SENSIBLE HEAT RECEIVER

ITP_JEC91-001.9



SPACE ENERGY CONVERSION R&T

THERMAL ENERGY CONVERSION

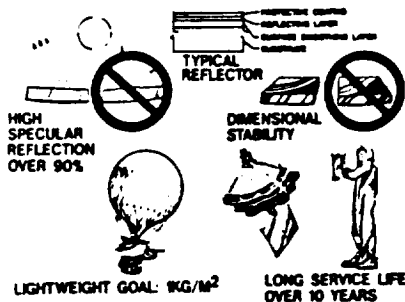
ADVANCED CONCENTRATORS

OBJECTIVES

DEVELOP FABRICATION PROCESS TECHNOLOGY FOR:

- ACCURATE SURFACE CONTOURS (1 MILLIRADIAN)
- HIGH SPECULAR REFLECTION (90%)
- LOW SPECIFIC MASS (1-2 kg/m²)
- HIGH CONCENTRATION RATIO (2000-5000)

REFLECTOR RESEARCH OBJECTIVES



HIGHLY SPECULAR ALL ALUMINUM REFLECTOR PANEL

MILESTONES

- 1992 COMPLETE DEVELOPMENT OF ALL METAL FABRICATION TECHNIQUES

ITP_JEC91-001.10



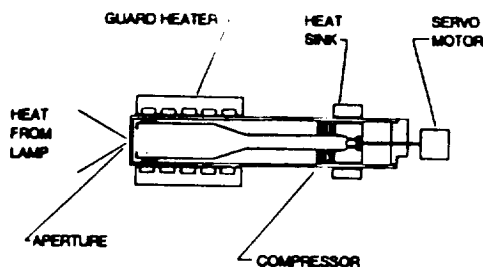
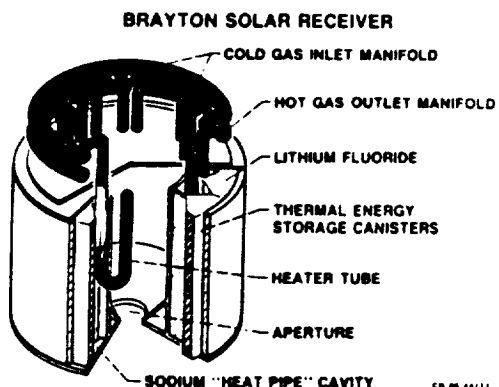
SPACE ENERGY CONVERSION R&T

THERMAL ENERGY CONVERSION

ADVANCED RECEIVERS

OBJECTIVES

DEVELOP HEAT RECEIVER TECHNOLOGIES THAT REDUCE THE MASS OF AVAILABLE TECHNOLOGY RECEIVERS BY AT LEAST A FACTOR OF 2



MILESTONES

- 1991 - COMPLETE INVESTIGATION OF A 0.5 kW_e BENCH TOP PROTOTYPE OF DIRECT FLUID ABSORPTION RECEIVER
- 1993 - COMPLETE TECHNOLOGY FEASIBILITY EXPERIMENTS FOR BRAYTON CYCLE HEAT RECEIVER
- 1995 - COMPLETE CRITICAL TECHNOLOGY EXPERIMENTS FOR SENSIBLE HEAT RECEIVER

ITP JEC91-001.11



SPACE ENERGY CONVERSION R&T

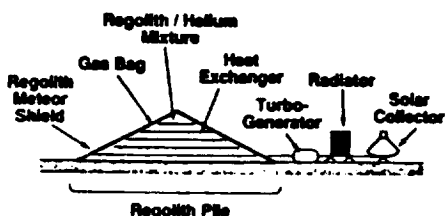
THERMAL ENERGY CONVERSION

THERMAL ENERGY STORAGE

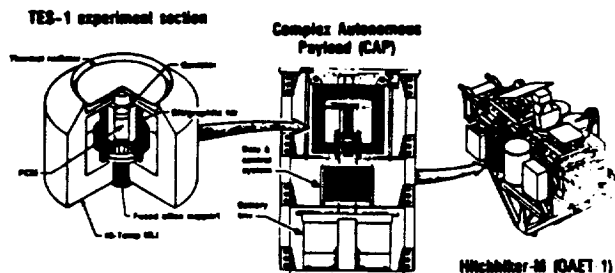
OBJECTIVES

- DEVELOP 3-D CODE FOR PREDICTING VOID FORMATION/MIGRATION IN TES MEDIA UNDER MICRO-GRAVITY CONDITIONS
- DEVELOP TECHNOLOGIES FOR UTILIZING LUNAR IN-SITU MATERIALS FOR TES

Regolith Thermal Energy Storage



THERMAL ENERGY STORAGE TECHNOLOGY EXPERIMENT



MILESTONES

- 1993 COMPLETE MODS TO THE NORVEX CODE TO COVER WEDGE GEOMETRY AND NON-WETTING MEDIA
- 1994 COMPLETE CRITICAL TECHNOLOGY EXPERIMENTS OF LUNAR TES CONCEPT

ITP JEC91-001.12



Thermal Energy Conversion

MAJOR ACCOMPLISHMENTS

DESIGN & ANALYSIS

- COMPARED PV AND SD POWER SYSTEMS (7 TO 35 kW RANGE) FOR AVAILABLE, NEAR TERM, & FAR TERM TECHNOLOGIES
- IDENTIFIED ENABLING TECHNOLOGIES FOR POTENTIAL LUNAR SURFACE POWER APPLICATIONS

ADVANCED CONCENTRATORS

- SELECTED SPLINED RADIAL PANELS & HINGED PETAL DEPLOYMENT CONCEPTS
- DEVELOPED FABRICATION PROCESSES FOR ALL METAL MIRROR SECTORS
 - STRETCH-FORM PANELS
 - SPRAY & SPIN COATED SURFACE LEVELIZING LAYERS
 - MICROSHEET GLASS FORMING & BONDING

ADVANCED RECEIVERS

- DESIGNED RECEIVERS FOR BRAYTON & STIRLING CONVERSION UNITS
- COMPLETED TES CRITICAL TECHNOLOGY EXPERIMENTS
 - UNIFORM FLUX WILL PRECLUDE THERMAL RATCHETING

THERMAL ENERGY STORAGE

- GERMANIUM & BORON NITRIDE ARE VIABLE TES MATERIALS
 - NO DEGRADATION AFTER 1000 CYCLES
- COMPLETED NORVEX CODE FOR LARGE VOLUME CHANGE TES MEDIA

ITP-JEC91-001.13

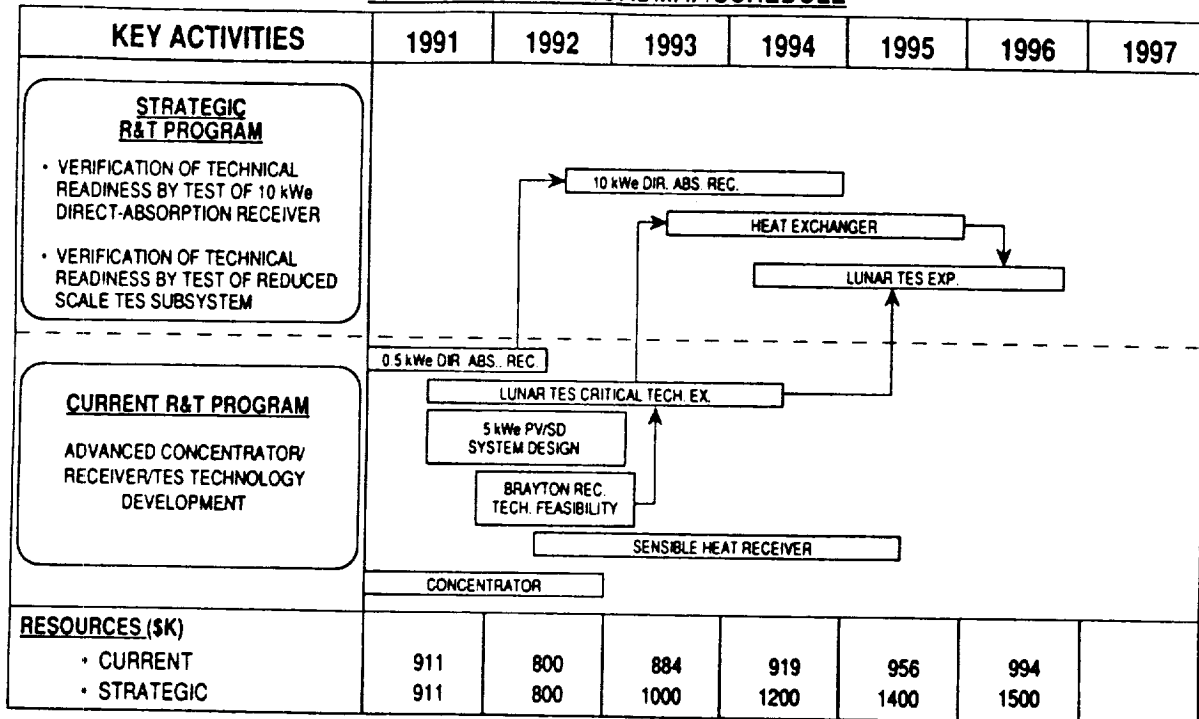


Thermal Energy Conversion

STRATEGIC PROGRAM* DESCRIPTION

* CONTAINS ALL ELEMENTS AND ASPECTS OF CURRENT PROGRAM PLUS:

- CONDUCT EXPERIMENTS TO DEMONSTRATE TECHNOLOGY READINESS OF CRITICAL SD COMPONENTS FOR LUNAR BASE APPLICATION
 - 10 kWe DIRECT ABSORPTION RECEIVER IN SANDIA ON-SUN FACILITY
 - REDUCED SCALE TES SUBSYSTEM IN RELEVANT ENVIRONMENT

**THERMAL ENERGY CONVERSION****SOLAR DYNAMIC ROADMAP/SCHEDULE**

ITP JEC91-001.15

**THERMAL ENERGY CONVERSION****RELATED EFFORTS**

- IN-STEP TEST FLIGHT EXPERIMENTS
- CSTI HIGH CAPACITY POWER PROJECT
- DOD/AF SPACE POWER PROGRAMS
- DOE TERRESTRIAL SOLAR POWER PROGRAM

ITP JEC91-001.16

SPACE ENERGY CONVERSION BASE R&T
THERMAL ENERGY CONVERSION

OAET

SUMMARY

• **TECHNICAL CHALLENGE:**

DEVELOP HIGH EFFICIENCY, STATIC THERMAL-TO-ELECTRIC CONVERSION TECHNOLOGIES TO REDUCE THE MASS AND FUEL INVENTORY IN RADIOISOTOPE BASED SPACE POWER SYSTEMS. IMPROVE THE EFFICIENCY, RELIABILITY AND LIFE, AND REDUCE THE MASS OF SPACE SOLAR DYNAMIC POWER SYSTEMS.

• **APPROACH:**

DEVELOP ADVANCED THERMOELECTRIC MATERIALS, AND AMTEC, FOR STATIC, RADIOISOTOPE-BASED POWER SYSTEMS. INVESTIGATE OTHER STATIC CONVERSION CONCEPTS AS WARRANTED. FOR SOLAR DYNAMIC SYSTEMS, FOCUS ON FABRICATION PROCESSES FOR CONCENTRATORS, HEAT PIPE RECEIVER CONCEPTS, AND UTILIZATION OF IN-SITU MATERIALS FOR TES.

• **PAYOFF:**

HIGH EFFICIENCY STATIC CONVERSION COULD REDUCE RADIOISOTOPE FUEL INVENTORY BY FACTORS OF 2-5, THUS SIGNIFICANTLY REDUCING FUEL COSTS, AND REDUCING MASS AND VOLUME. FOR SOLAR DYNAMIC, REDUCED ORBITAL SYSTEM MASS BY 50% AND TRANSPORTED LUNAR MASS BY FACTORS OF 2-5 ARE THE PAYOFFS.

• **RATIONALE FOR AUGMENTATION:**

ENABLES TRANSFER OF STATIC CONVERSION TECHNOLOGY INDUSTRY. EXPANDS CURRENT SOLAR DYNAMIC PROGRAM TO INCLUDE VERIFICATION OF LUNAR BASE RECEIVER, LUNAR BASE TECHNOLOGIES.

• **TECHNOLOGY CONTRIBUTIONS:**

THERMOELECTRIC MATERIALS MODELING CAPABILITIES UTILIZED IN HIGH CAPACITY POWER/SP-100 PROGRAMS. ALL-METAL SOLAR CONCENTRATOR TECHNOLOGIES INCORPORATED BY SSF PROGRAM IN FY90.

ITP JEC91-001.17

INTEGRATED TECHNOLOGY PLAN
FOR THE CIVIL SPACE PROGRAM

SPACE ENERGY CONVERSION R&T PROGRAM

POWER MANAGEMENT

JUNE, 1991

Office of Aeronautics, Exploration and Technology
National Aeronautics and Space Administration

Washington, D. C.

RWB-91Q.04.1

BASE R&T: SPACE ENERGY CONVERSION

POWER MANAGEMENT

OBJECTIVES

- **PROGRAMMATIC**
 - DEVELOP AND DEMONSTRATE RELIABLE, LIGHTWEIGHT, EFFICIENT COMPONENTS AND SYSTEMS FOR THE MANAGEMENT AND DISTRIBUTION OF ELECTRICAL POWER FOR A BROAD SPECTRUM OF SPACE SYSTEMS
- **TECHNICAL**
 - UTILITY POWER FOR SPACE, EXPLORATION POWER, INTEGRATED CIRCUITS (PIC), ADVANCED POWER MATERIALS, ENVIRONMENTAL INTERACTION MODELS/GUIDELINES, HIGH TEMPERATURE POWER ELECTRONICS

SCHEDULE

- 1993 - SAMPLE SHUTTLE EXPERIMENT LAUNCH
DEMONSTRATE 200°C BASEPLATE INVERTER
- 1994 - COMPLETE TECHNOLOGY DEMONSTRATION FACILITY
- 1995 - PROTOTYPE SMART POLE PIC
1ST IC SYNCH. RECTIFIER PROTOTYPE
- 1996 - EPSAT BASED INTERACTIONS CODES DONE
300°C COMPONENTS COMPLETE
ADVANCED SYNCH. RECTIFIER PIC
- 1997 - SPACE POWER SYSTEMS DESIGN GUIDELINES
DEMONSTRATE HIGH THERMAL CONDUCTIVITY
GRAPHITE-FLORIDE CIRCUIT BOARD
UTILITY POWER DEMONSTRATION

RESOURCES (\$M)

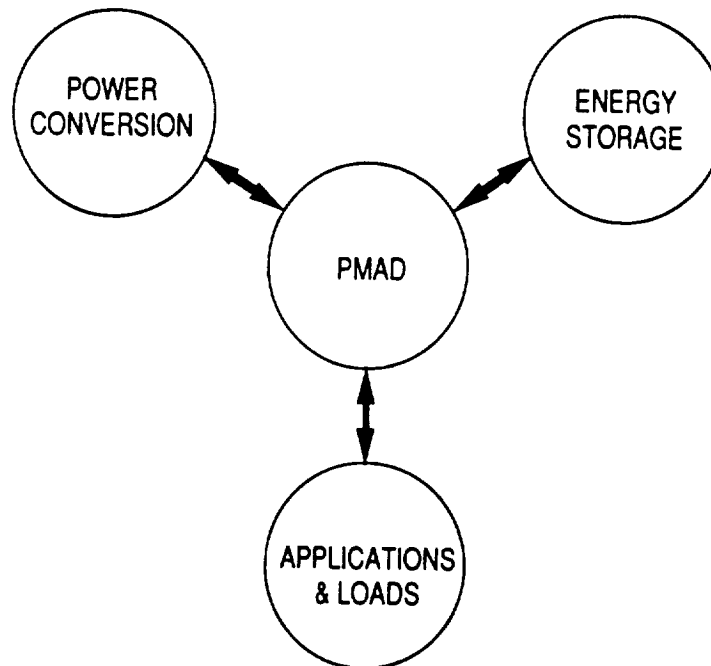
	BASLINE	STRATEGIC
• FY		
• 1991	1.30	1.30
• 1992	1.17	1.17
• 1993	1.24	1.82
• 1994	1.30	2.08
• 1995	1.37	2.41
• 1996	1.43	2.67
• 1997	1.50	2.99

PARTICIPANTS

- **LEWIS RESEARCH CENTER**
RESPONSIBILITIES: ELECTRICAL POWER MANAGEMENT
POWER MATERIALS
SPACE ENVIRONMENT
- **JET PROPULSION LABORATORY**
RESPONSIBILITIES: POWER INTEGRATION TECHNOLOGY

POWER MANAGEMENT AND DISTRIBUTION

PERFORMS ALL POWER SYSTEM FUNCTIONS OTHER THAN
GENERATION AND STORAGE



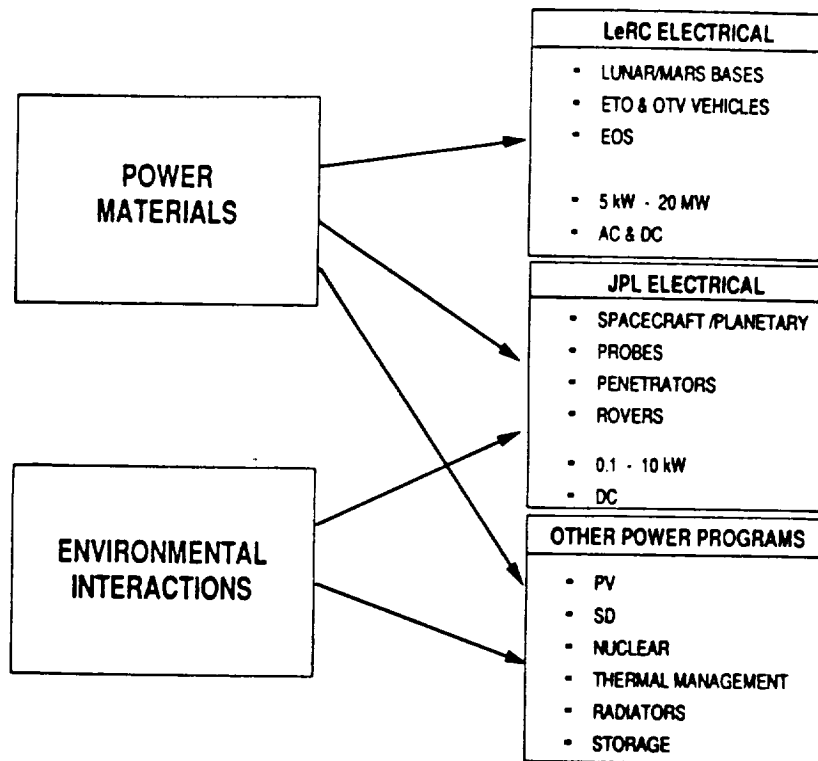
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TECHNOLOGY NEEDS

- **ADVANCED POWER MANAGEMENT TECHNOLOGY FOR THE FULL RANGE OF SPACE AND PLANETARY MISSIONS, INCLUDING:**
 - **LUNAR AND MARS BASES**
 - COMPLEX, EVOLUTIONARY SYSTEMS COMPARABLE TO TERRESTRIAL UTILITIES
 - SURVIVE UNIQUE, HOSTILE ENVIRONMENTS, INCLUDING HIGH TEMPERATURES & CHARGED DUST, CORROSIVE ATMOSPHERE & GEOTAIL
 - AUTONOMOUS OPERATION
 - **ADVANCED SCIENCE MISSIONS: EOS PLATFORMS, PLANETARY SPACECRAFT, ETC.**
 - RELIABLE, LIGHTWEIGHT SPACECRAFT POWER
 - REDUCED PARTS COUNT (75%)
 - REDUCED VOLUME (40%)
 - REDUCED MASS (50%)
 - EOS PLATFORMS: HIGH POWER & DURABLE PV BLANKETS
 - SOLAR PROBE AND MDO: VERY HIGH TEMPERATURE OPERATION
 - **LAUNCH AND ORBITAL TRANSFER VEHICLES**
 - REPLACEMENT OF HYDRAULICS WITH ELECTRICAL ACTUATORS
 - LIGHTWEIGHT INTEGRATED POWER SYSTEM
 - VEHICLE HEALTH MANAGEMENT
 - STS EVOLUTION
 - NUCLEAR ELECTRIC PROPULSION - LIGHTWEIGHT ELECTRICAL SUBSYSTEM
 - **ENVIRONMENTALLY COMPATIBLE POWER SYSTEM**
 - PV
 - NUCLEAR & SOLAR DYNAMIC

RWB-91Q.04.9

PROGRAM ELEMENT INTERACTIONS



RWB-91Q.04.8

TECHNOLOGY DEVELOPMENT CHALLENGE

POWER MANAGEMENT IS CHARACTERIZED BY:

COMPLEX ISSUES

- ELEMENT OF ALL SPACE SYSTEMS
 - DIVERSE REQUIREMENTS
- UNIQUE, HOSTILE ENVIRONMENTS
- REQUIRES MULTIPLE TECHNOLOGIES
 - MATERIALS
 - COMPONENTS
 - SYSTEM
- NEW MISSIONS

COMPLEX INFRASTRUCTURE

- BROAD R&D BASE
 - NASA
 - OTHER AGENCIES
 - INDUSTRY
 - OTHER NATIONS
- EXTENSIVE VENDOR BASE
 - SPACE
 - AERONAUTICS & MILITARY
 - COMMERCIAL
- SPACE IS MINOR MARKET

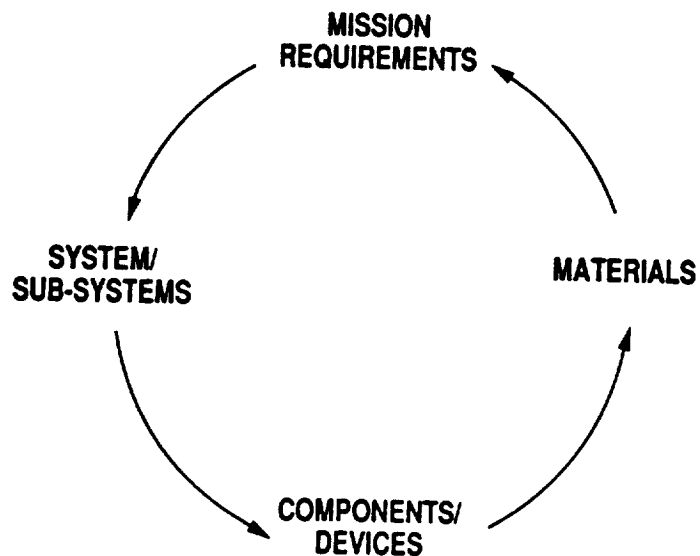
POWER MANAGEMENT MUST MAKE SIGNIFICANT IMPACT ON NASA PROGRAMS

WITH LIMITED BUDGET AND STAFFING

TECHNOLOGY DEVELOPMENT APPROACH

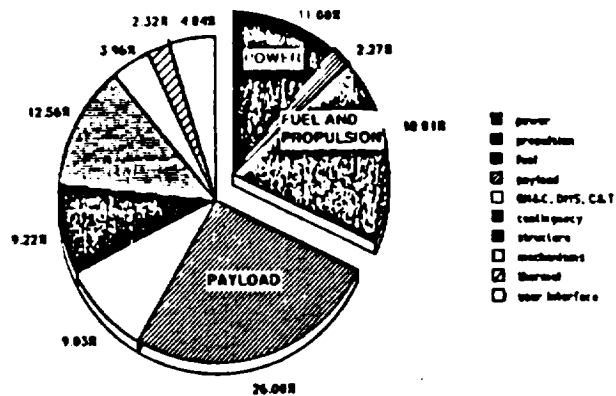
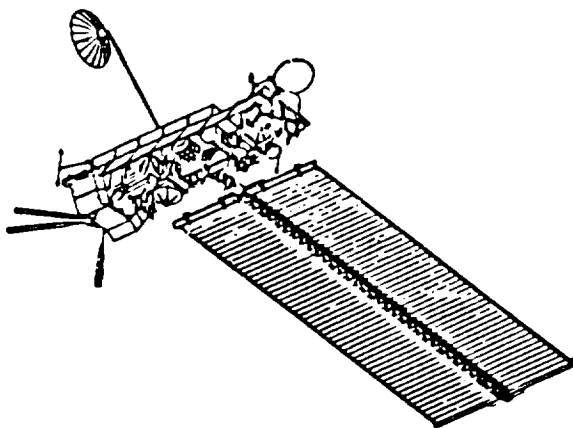
- IDENTIFY CRITICAL ISSUES AND BENEFITS THROUGH PMAD SYSTEMS ANALYSIS
- AUGMENT RESOURCES THROUGH SPECIFIC TASK ASSIGNMENTS ON RELEVANT SUBJECTS
- LEVERAGE OTHER R&D EFFORTS AND COMMERCIAL DEVELOPMENTS THROUGH SPECIFIC PROJECT EFFORTS
- MAINTAIN CLOSE COMMUNICATIONS WITH TECHNOLOGY AND USER GROUPS IN NASA, OTHER AGENCIES AND INDUSTRY

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NASA Earth Observing System OAST

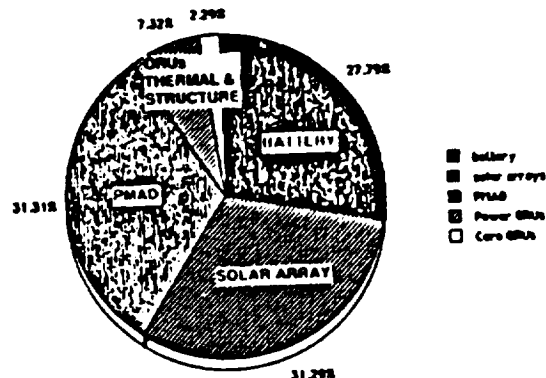
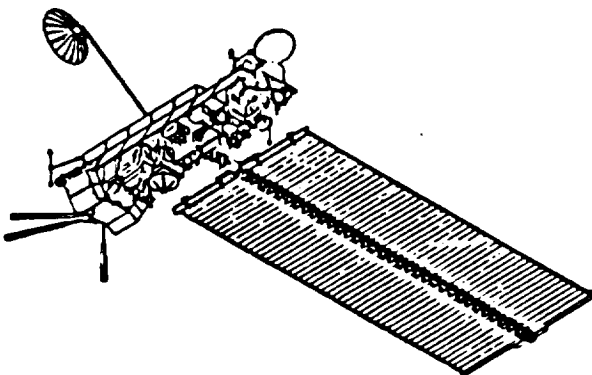
POLAR ORBITING PLATFORM WET MASS



TOTAL WEIGHT IS 29715 lbs (13507 kg)

NASA Earth Observing System OAST

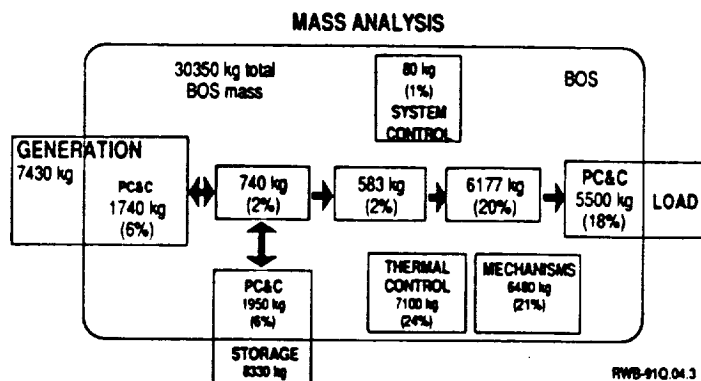
ELECTRICAL POWER SYSTEM WEIGHTS



TOTAL EPS WEIGHT IS 3264.8 lbs (1484 kg)

SPACE STATION FREEDOM

- PERMANENTLY MANNED, MULTI-PURPOSE, SPACE BASED FACILITY
- POWER HALF THE COST OF SSF
 - WP - 1
 - WP - 2
 - WP - 4
- POWER CONDITIONING, CONTROL AND DISTRIBUTION (PCC&D) MASS > GENERATION & STORAGE MASS
- BALANCE OF SYSTEM IS 2/3 OF POWER SYSTEM MASS
- MAJOR DISPUTES OVER POWER DISTRIBUTION CONVENTIONS
 - HIGH VOLTAGE DC
 - 400 Hz AC
 - 20 kHz AC
 - "WILD FREQUENCY" AC
- DIFFERENT CONCEPTS
 - EXTENSION OF SPACECRAFT TECHNOLOGY
 - SPACE POWER UTILITY

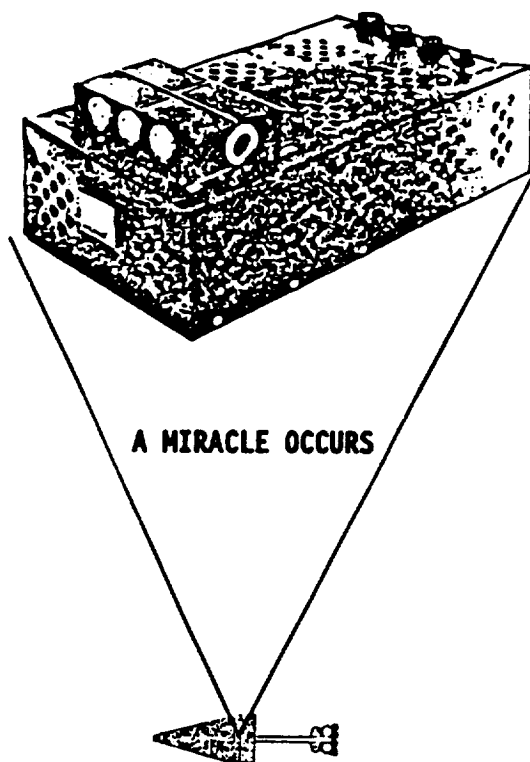


ALTITUDE TECHNOLOGY DIRECTORATE

POWER TECHNOLOGY DIVISION



Lewis Research Center



A MIRACLE OCCURS

POWER PROCESSING,
CONTROLS, AND
DISTRIBUTION

STATE-OF-THE-ART

25-100 kg/kWe

PILOTED MARS
NEP VEHICLE

TOTAL

5-10 kg/kWe

OTHER DEVELOPMENT EFFORTSPOWER INTEGRATION TECHNOLOGY

- SOLID STATE POWER SWITCH HYBRID FOR THE CRAFT AND CASSINI SPACECRAFT
 - HIGH RELIABILITY
 - 90 WATT DELIVERED TO LOAD
- SMART POLE HYBRID FOR 15 HP ELECTRICAL ACTUATOR
 - AIR FORCE PROGRAM 1988 - 1990
- SMART POLE HYBRID FOR PV POWER CONDITIONING
 - DOE FUNDED: AUGUST 1991 START

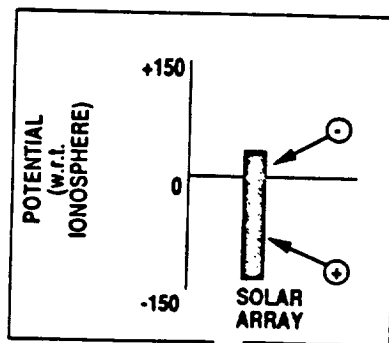
SPACE ENVIRONMENT

- EPSAT ENGINEERING CODE
 - SDIO SPONSORED
 - EMPHASIS ON MILITARY PLATFORMS
 - SURVIVABILITY KEY GOAL
 - COMPLETE IN FY 1992
- ENVIRONMENT WORKBENCH
 - EPSAT DERIVATIVE
 - SSF FUNDED, MINIMALLY
 - SPACE STATION SPECIFIC
 - COMPLETION REQUIRES LARGE INCREASE IN SSF FUNDING

RWB-91Q.04.23

**PLASMA EFFECTS IDENTIFIED AS CRITICAL FOR SSF
MOTIVATED ENGINEERING CHANGE**

- ARRAY "FLOATS" WITH 90% OF AREA BELOW PLASMA POTENTIAL
 - SSF USES NEGATIVE GROUNDING
 - SUBJECTS MODULE SURFACES TO 140 eV IONS
 - ANODIZED AL SPUTTERS, BREAKS DOWN
- SSF ELECTRICAL GROUNDING TIGER TEAM CONVENED
 - CONFIRMED EFFECTS
 - EVALUATED GROUNDING CHANGES OR OTHER WAYS TO REDUCE SSF FLOATING POTENTIAL
 - EPSAT-BASED CODE (EWB) MADE DESIGN TRADES EASY
 - RECOMMENDED PLASMA CONTACTOR TO CONTROL POTENTIALS
 - CONSIDERING ARRAY REDESIGN TO REDUCE ELECTRON CURRENT COLLECTION - LARC NASCAP/LEO MODELING RESULT



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OTHER DEVELOPMENT EFFORTS (con'td)ELECTRICAL COMPONENTS AND SYSTEMS

- SYSTEMS DIAGNOSTICS, RADIATION TOLERANT SWITCHES AND HIGH TEMPERATURE MAGNETICS
 - CSTI - HIGH CAPACITY POWER
- STIRLING LINEAR ALTERNATOR - PC&C
 - CSTI - HIGH CAPACITY POWER
- NASA WIRING STUDY (KAPTON REPLACEMENT)
 - CODE - Q
- HIGH FREQUENCY LINK AND ELECTRIC ACTUATORS
 - ALS AND CODES R-M BRIDGING TECHNOLOGY
 - NLS AND SHUTTLE UPGRADES
- MORE ELECTRIC AIRPLANE
 - CODE RP & DOD
- AUTONOMOUS POWER SYSTEM & EXPERT SYSTEMS
 - CSTI - ARTIFICIAL INTELLIGENCE
- SYSTEMS ANALYSIS (SCIENCE)
 - CODE RS
- MULTI-MEGAWATT INVERTER TECHNOLOGY
 - USAF
- SPACE BASED TESTBED (SC-2000)
 - CODE C

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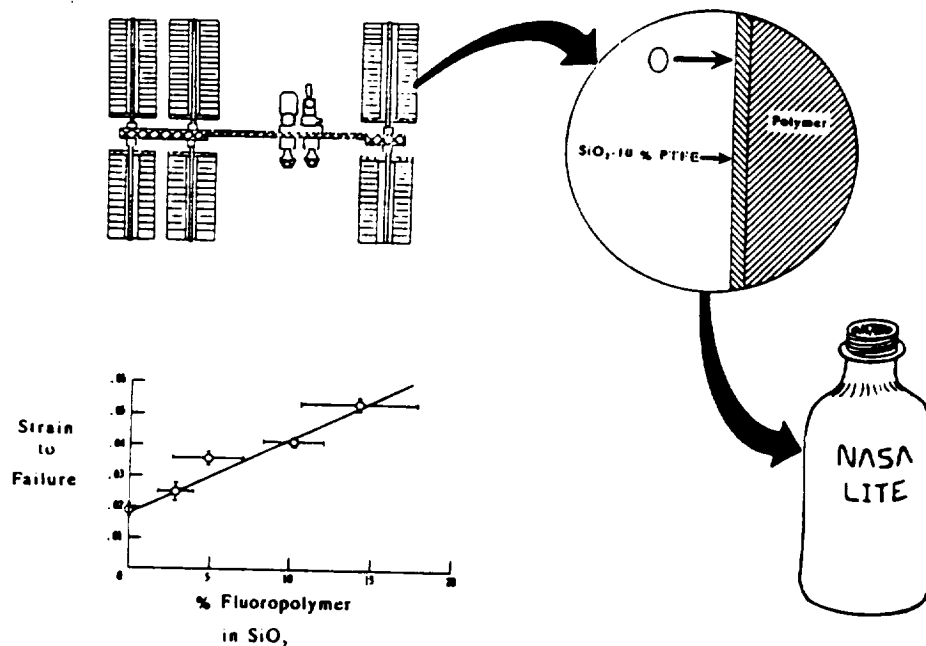
OTHER DEVELOPMENT EFFORTS (con'td)POWER MATERIALS

- SPACE POWER MATERIALS TECHNOLOGY
 - CODE RP
- HIGH EMITTANCE RADIATOR SURFACES FOR SP-100
 - CODE RP
- DIAMOND THIN FILMS
 - SDIO
- PV ARRAY ATOMIC OXYGEN PROTECTION
 - SSF: ARRAY PROTECTION SYSTEM ADOPTED
- PV POWER MODULE RADIATOR SURFACE LEO DURABILITY
 - SSF: RECOMMENDED MODIFICATIONS ADOPTED
- SPACE STATION FREEDOM ARRAY MATERIALS EROSION FLIGHT EXPERIMENT ON EOIM III
 - SSF
- PV ARRAY FLEXIBLE CIRCUIT CARRIER KAPTON PYROLIZATION
 - SSF

OTHER DEVELOPMENT EFFORTS (con'td)

- LEO ENVIRONMENTALLY DURABLE MATERIALS
 - CODE RM
- NASA ATOMIC OXYGEN EFFECTS TEST PROGRAM
 - CODE RM
- LDEF POST RETRIEVAL ANALYSIS
 - CODE RM
- PARA-TO-ORTHO HYDROGEN CONVERSION CATALYTIC SURFACES
 - NASP
- DIAMOND-LIKE FILMS FOR OPHTHALMIC LENS PROTECTION
 - TECHNICAL UTILIZATION
- OXYGEN DIFFUSION BARRIER COATINGS FOR BEVERAGE CONTAINERS
 - EASTMAN CHEMICAL CO.

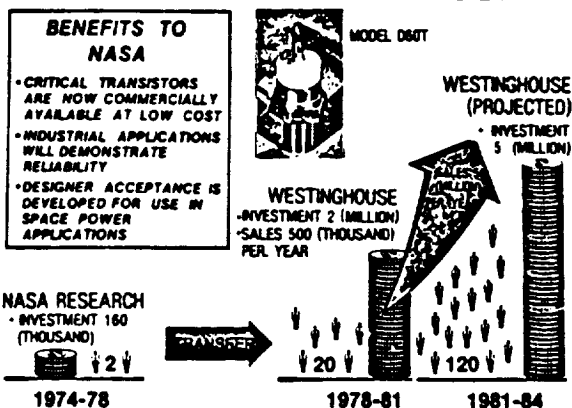
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SPINOFF APPLICATIONS OF
FLEXIBLE ATOMIC OXYGEN PROTECTIVE COATINGS

POWER MANAGEMENT

DEVELOPMENT OF TECHNOLOGY INFRASTRUCTURE FOR NASA MISSIONS

NASA—LeRC POWER TRANSISTOR TECHNOLOGY TRANSFER



- NASA MINOR PLAYER IN POWER AND CONTROL ELECTRONICS INDUSTRIES
 - REQUIRED TECHNOLOGY ONLY AVAILABLE IF THERE IS AN INDUSTRIAL BASE
- OAET CAN IMPACT BASE THROUGH JUDICIOUS SEED PROJECTS
 - D60T AND OTHER POWER TRANSISTORS NOW IN WIDE USE BY NASA, DoD AND INDUSTRY
 - MCT NOW ENTERING PRODUCTION AFTER JOINT SPONSORSHIP BY NASA, DoD AND EPRI

BASE R&T: SPACE ENERGY CONVERSION

POWER MANAGEMENT

TECHNOLOGY CHALLENGES

SPACECRAFT POWER MANAGEMENT

- ADVANCED, "CONVENTIONAL" SPACECRAFT: PLANETARY, EOS, ATRSS, ETC.
- OBJECTIVE: EXTEND MISSION LIFE, REDUCE POWER & PROPULSION SYSTEM MASSES AND INCREASE (SCIENCE) DATA RETURN

POWER FOR ADVERSE ENVIRONMENTS

- LUNAR/MARS BASES, SELF-INDUCED ENVIRONMENTS
- OBJECTIVE: DEVELOP HIGH TEMPERATURE, RADIATION TOLERANT POWER ELECTRONICS AND RESOLVE OTHER ENVIRONMENTAL HAZARDS

UTILITY POWER

- MANNED SYSTEMS, SPACE EXPLORATION INITIATIVE
- OBJECTIVE: PROVIDE SPACE SYSTEMS WITH THE SAFETY, FLEXIBILITY, MAINTAINABILITY AND USER TRANSPARENCY NOW FOUND ONLY IN TERRESTRIAL POWER UTILITIES

SPACECRAFT POWER MANAGEMENTOBJECTIVE:

EXTEND MISSION LIFE, REDUCE POWER & PROPULSION SYSTEM MASSES AND INCREASE (SCIENCE) DATA RETURN

- ADVANCED, "CONVENTIONAL" SPACECRAFT: PLANETARY, EOS, ATRSS, ETC.

APPROACH/BENEFITS:

- **POWER INTEGRATED CIRCUITS**
 - REDUCE PARTS COUNT BY 75% (INCREASED RELIABILITY)
 - REDUCE WEIGHT BY 50%
 - REDUCE VOLUME BY 40%
 - INCREASED POWER DENSITY (X10) AND INCREASE EFFICIENCY
- **INTERCALATED GRAPHITE ELECTRONIC ENCLOSURES**
 - EQUIVALENT TO METAL BOXES FOR EMI SHIELDING AND STRENGTH
 - 1/2 - 1/4 WEIGHT OF METAL - STRUCTURES/MECHANISMS 20% OF POWER SYSTEM MASS
- **EOS: ATOMIC OXYGEN PROTECTIVE COATINGS FOR SOLAR ARRAYS IN LEO**
 - KAPTON SUBSTRATE MASS LOSS < 50% OVER 15 YEARS

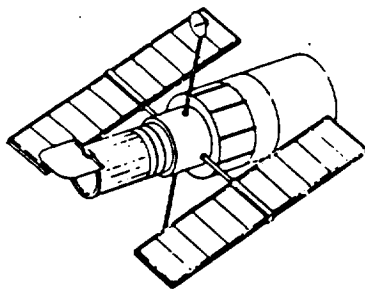


AEROSPACE TECHNOLOGY DIRECTORATE

POWER TECHNOLOGY DIVISION



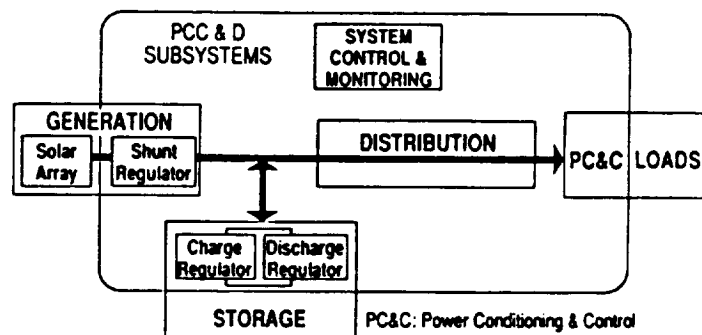
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CONVENTIONAL SPACECRAFT POWERSYSTEM DRIVERS

- DEDICATION MISSION
- MINIMUM MASS
- HIGH RELIABILITY
 - MINIMAL ON-ORBIT REPAIR

MULTIPLE, INCOMPATIBLE, "STANDARD" BUSES

- **GENERATION: SOLAR ARRAY OR RTG**
- **STORAGE: BATTERIES**
- **POWER CONDITIONING CONTROL AND DISTRIBUTION**
 - SINGLE/DUAL BUS
 - FULL, SUNLIGHT OR UNREGULATED
 - SHUNT OR PEAK POWER TRACKER
 - 28-50 VDC



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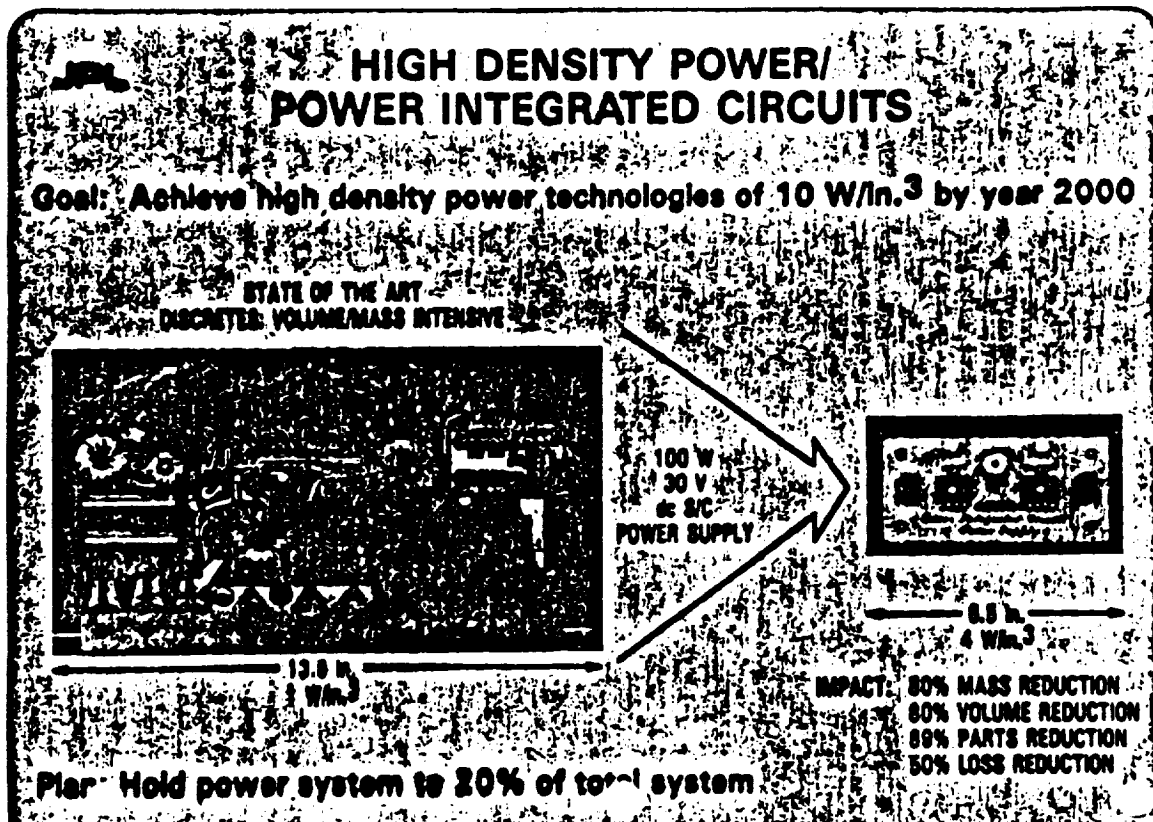
OAET

POWER INTEGRATION TECHNOLOGY

STATE OF THE ART ASSESSMENT

- **GENERAL ASSESSMENT: CURRENT GENERIC POWER MODULES ARE OF VERY LIMITED UTILITY (e.g. low power, simple functions), LOW AVERAGE EFFICIENCIES, WILL NOT MEET SPACE APPLICATION REQUIREMENTS.**
- **DETAILED ASSESSMENT:**
 - CURRENT HYBRID MODULES ARE DRIVEN BY THE AUTOMOBILE INDUSTRY FIRST, PC INDUSTRY SECOND
 - CURRENT, MULTI-FUNCTION or SMART, HYBRID MODULES ARE LIMITED IN POWER DELIVERY (e.g. 30 WATTS DISSIPATION)
 - HYBRID TECHNOLOGY IS NOT READY TO SUPPORT THE THERMAL NEEDS OF A SPACE BOUND DEVICE
 - MONOLITHIC TECHNOLOGY FOR POWER INTEGRATED CIRCUITS IS LIMITED TO LOW POWER (1 TO 3 WATTS)
 - MONOLITHIC PROCESSING OF POWER INTEGRATED CIRCUITS, INTEGRATING HIGH POWER AND CONTROL FUNCTIONS, IS NOT A MATURE TECHNOLOGY

JUNE 26, 1991

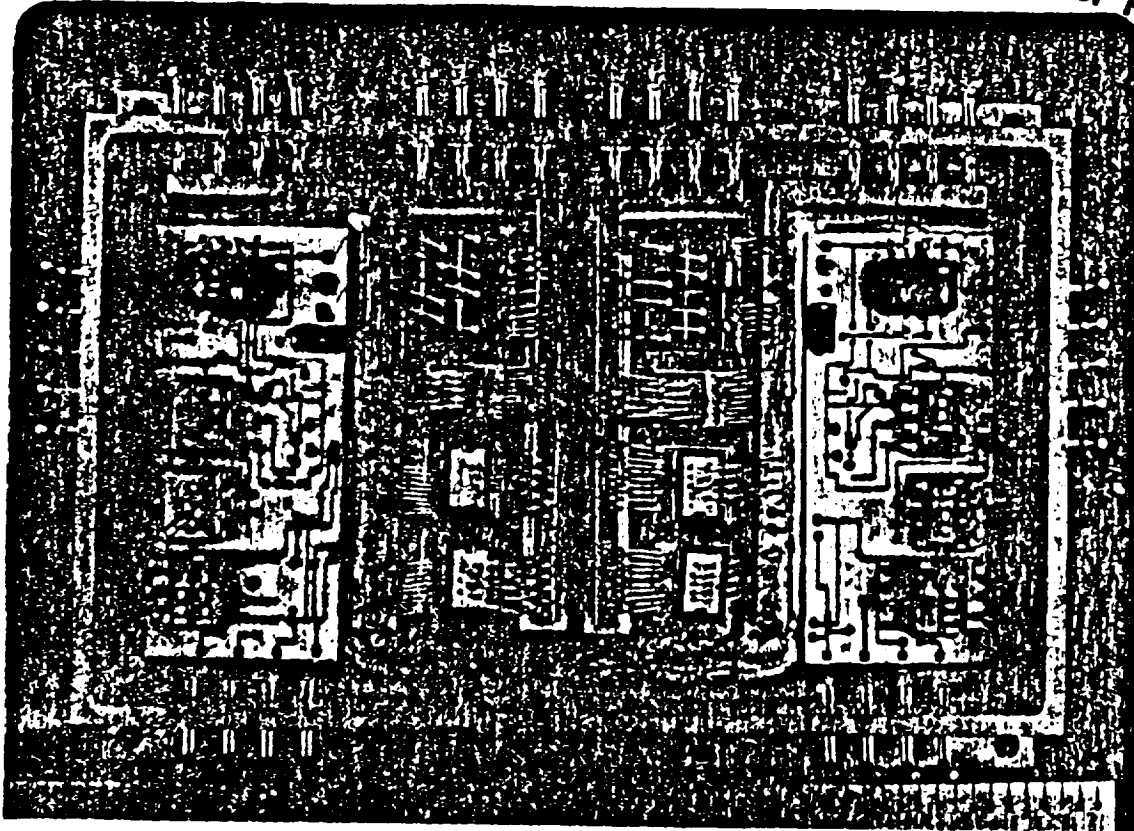


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OF POOR QUALITY

PROTO HYBRID POWER SWITCH

WESTINGHOUSE FOUNDRY 2 SWITCHES, DRIVERS AND INTERFACE ICs

ORIGINAL PAGE IS
OF POOR QUALITY



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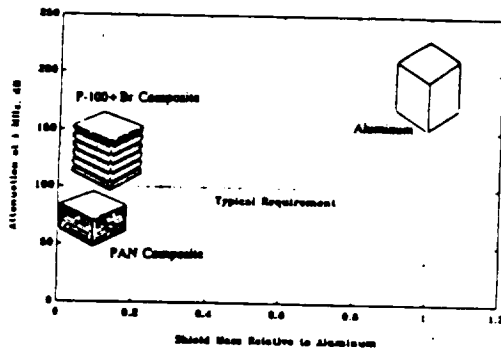
Advanced Technology Directorate

POWER TECHNOLOGY DIVISION

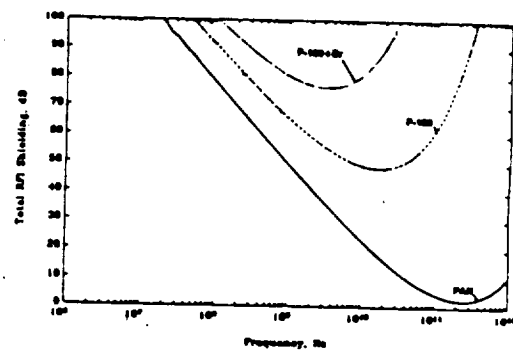
NASA

Lewis Research Center

INTERCALATED GRAPHITE COMPOSITE EMI SHIELDS



METALLIC SHIELDING -- COMPOSITE WEIGHT

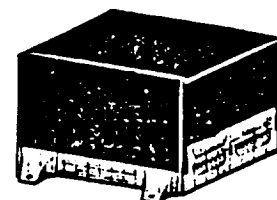
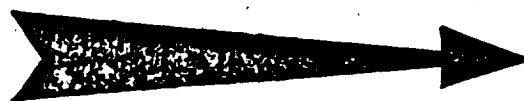
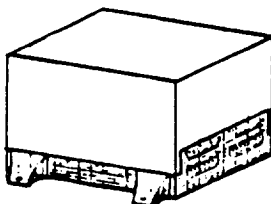


AT LEAST 80 DB SHIELDING/MM THICKNESS

80 PERCENT REDUCTION IN SHIELD MASS

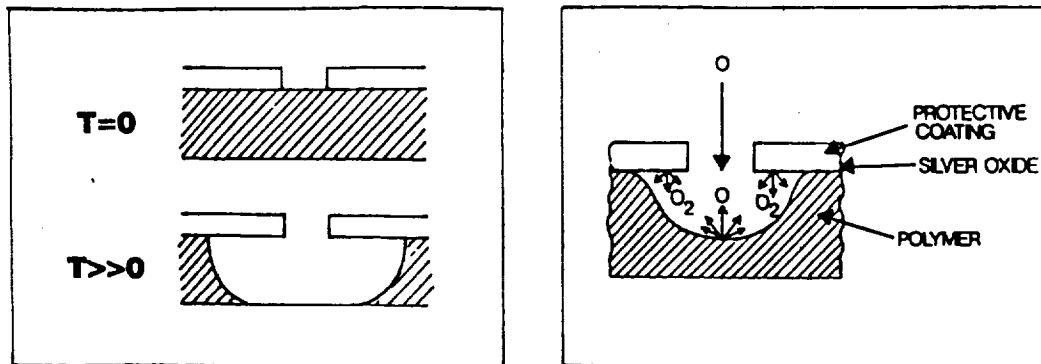
16 PERCENT REDUCTION IN POWER SYSTEM MASS

UP TO 40 PERCENT PAYLOAD INCREASE



COMPARED TO STANDARD ALUMINUM EMI COVERS

ATOMIC OXYGEN PROTECTIVE COATINGS FOR LOW EARTH ORBIT POWER SYSTEM SURFACES



ATOMIC OXYGEN ATTACK

- 0 OCCURS AT DEFECTS IN COATING
- 0 RESULTS IN LARGE AREA OF DAMAGE
- 0 OPTICAL THEN MECHANICAL DEGRADATION

RECOMBINATIVE PROTECTIVE COATINGS

- 0 COATING CATALYSES $2O \rightarrow O_2$ REACTION
- 0 LIMITS UNDERCUTTING DAMAGE

50% REDUCTION IN SOLAR ARRAY BLANKET MASS

BASE R&T: SPACE ENERGY CONVERSION

POWER MANAGEMENT

POWER FOR ADVERSE ENVIRONMENTS

OBJECTIVE:

- DEVELOP HIGH TEMPERATURE, RADIATION TOLERANT POWER ELECTRONICS AND RESOLVE OTHER ENVIRONMENTAL HAZARDS
 - LUNAR/MARS BASES
 - SELF-INDUCED ENVIRONMENTS

APPROACH/BENEFITS:

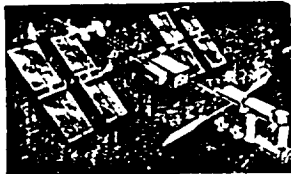
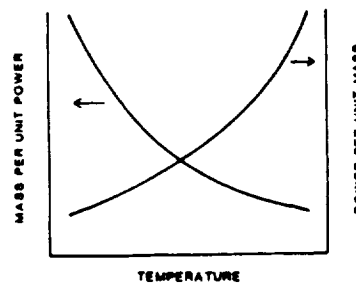
- DEVELOP RADIATION-HARD, HIGH-TEMPERATURE POWER ELECTRONICS: MATERIALS, DEVICES AND SYSTEMS
 - ALLOW OPERATION ON LUNAR SURFACE WITHOUT NEED FOR INSULATED ENCLOSURES AND HEAT PUMPS
 - REDUCE SIZE AND MASS OF LOW TEMPERATURE RADIATOR BY FACTOR OF 2 OR MORE
 - ENABLE NUCLEAR AND SD POWER SYSTEMS
- MODEL INTERACTIONS BETWEEN POWER SYSTEMS AND VARIOUS SPACE PLASMAS AND GASES
 - AVOID DISABLING ELECTRICAL DISCHARGES AND SYSTEM DEGRADATION
 - PROVIDE ENVIRONMENTAL GUIDANCE TO SYSTEM DESIGNERS
- AVOID DAMAGE AND SYSTEM DEGRADATION DUE TO LUNAR AND MARS DUST
 - WIND AND OTHER ABRASION
 - SHADOWING OF SOLAR ENERGY COLLECTIONS AND RADIATOR SURFACES

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HIGH TEMPERATURE ELECTRONICS PROGRAM

GOALS

- REDUCE RADIATOR WEIGHT IN SPACE SYSTEMS BY RAISING OPERATING TEMPERATURE FROM 100°C TO 300°C
- HOSTILE ENVIRONMENT TOLERANCE
- IMPROVE RELIABILITY AND LIFETIME
- HIGHER ENERGY DENSITIES
- LESS THERMAL MANAGEMENT REQUIREMENTS
- REDUCE LAUNCH COST



TECHNOLOGICAL DEVELOPMENTS

- ADVANCED MATERIALS: DIELECTRICS, INSULATION, SEMICONDUCTOR, MAGNETICS
- COMPONENTS: CAPACITORS, INDUCTORS, SWITCHES, TRANSISTORS, CABLES, TRANSFORMERS, CIRCUIT BOARDS, INVERTERS, GENERATORS, COMPUTERS

APPLICATIONS

- SPACE EXPLORATION AND DOD SYSTEMS
- SPACE NUCLEAR POWER
- ADVANCED AND CONVENTIONAL AIRCRAFT



AEROSPACE TECHNOLOGY DIRECTORATE

POWER TECHNOLOGY DIVISION



200°C-BASEPLATE ELECTRONICS

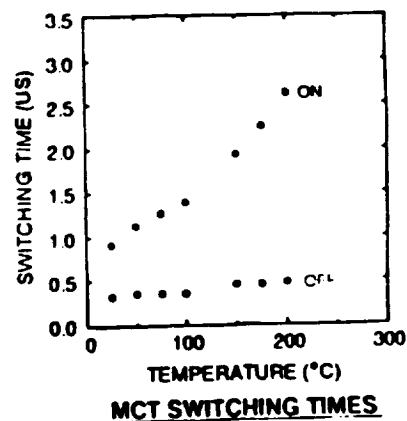
SURVIVES SEVERE ENVIRONMENTS AND LIGHTENS RADIATORS

GOAL: BUILD & TEST ASSEMBLY

- ACHIEVABLE (100°C > SOA)
- UNCOVERS MISSING TECHNOLOGY
- EXCEEDS LUNAR TEMPERATURE (130°C)
- REDUCES RADIATOR AREA > 2
- BROAD SPINOFFS



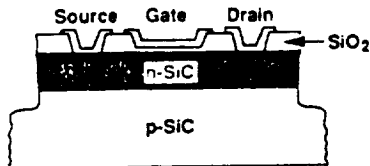
H. T. TEST LAB



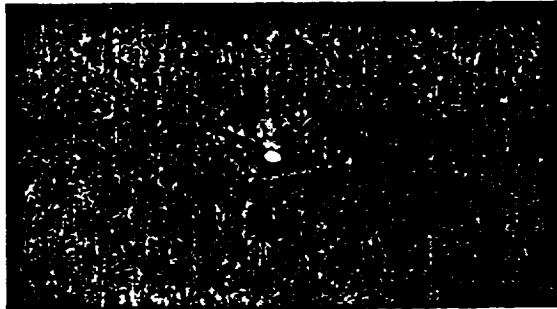
- SUNY/AUBURN GRANTS INITIATED
- COMPONENTS TESTED
 - MCT
 - CAPACITORS
 - INSULATION
- LABS SET UP
- CUSTOM COMPONENTS ORDERED

SILICON CARBIDE TECHNOLOGY FOR HIGH TEMPERATURE ELECTRONIC SWITCHES

Goal:
Develop and demonstrate a high temperature and radiation resistant SiC MOSFET power switch



SiC MOSFET Structure



Recently fabricated 6H-SiC grown junction light emitting diode operating at 600 °C

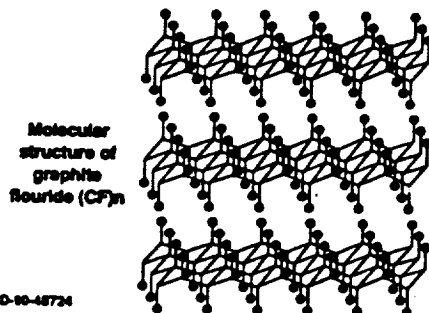
Accomplishments

- Demonstrated high quality 6H-SiC epitaxial film growth processes
- Demonstrated capability to dope 6H-SiC films p-type with aluminum
- Fabricated prototype 6H-SiC MOSFET and successfully tested to 500 °C

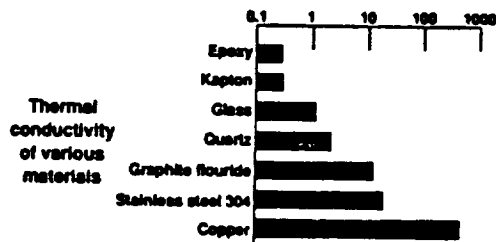
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GRAPHITE FLOURIDE HIGH THERMAL CONDUCTIVITY PRINTED CIRCUIT BOARDS

	Graphite fiber (P-100)	Graphite flouride (CF ₂) ₂	Fiber glass (S Glass)
Electrical resistivity (Ω cm)	2.5×10^{-4}	10^{11}	10^{14}
Thermal conductivity (W/m-K)	300	11	1.1
Young modulus (Msi)	105	25	12
Longitudinal tensile Strength (Ksi)	300	40	500
Coefficient of thermal expansion (CTE) (ppm/K)	-1	8	3
Density (g/cm ³)	2.18	2.5	2.5



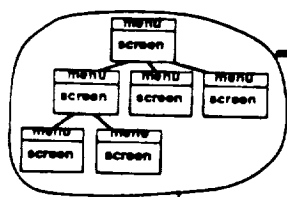
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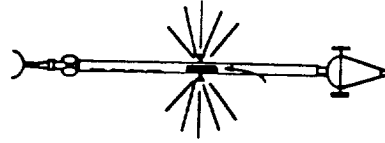


MAXWELL

EPSAT Environment - Power System Analysis Tool



EPSAT



System Design Tool For Large Space Based Power Systems

- System Analysis Of Complex Systems
- Incorporate Many Analysis Models
- Changeable As System Concepts Evolve

Technology Transfer

Scientists
and Engineers



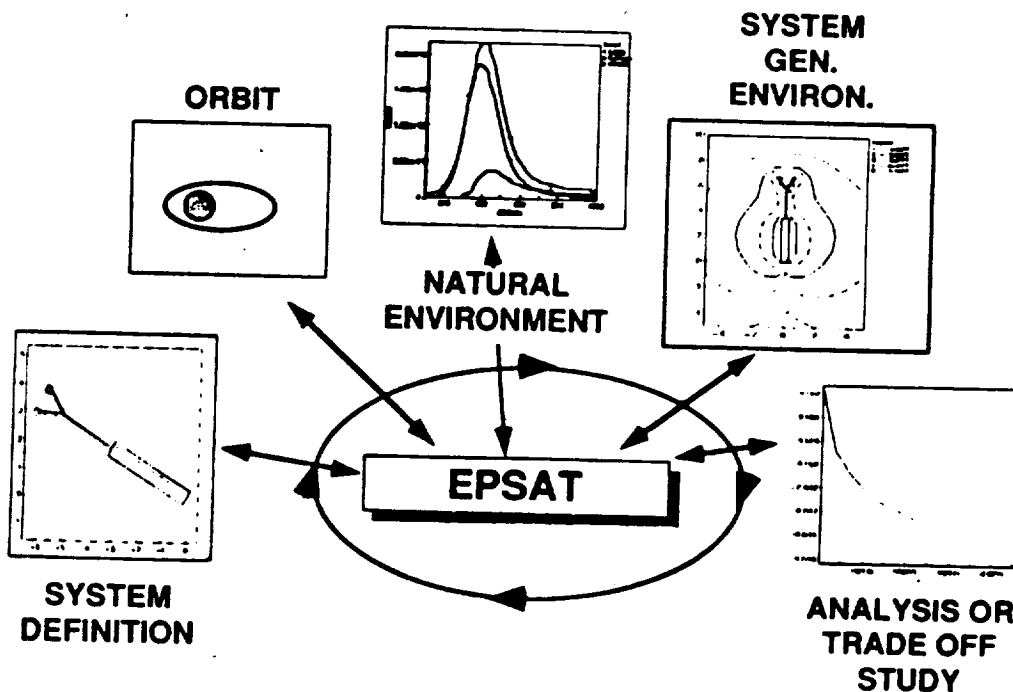
Power System
Design Engineers

NASA/Lewis 4/90



MAXWELL

EPSAT Performs Multi - Step Analysis By Connecting *Output* To *Input*



EPSAT - A FOUNDATION FOR SEI

• EPSAT DEVELOPED UNDER SDIO FUNDING

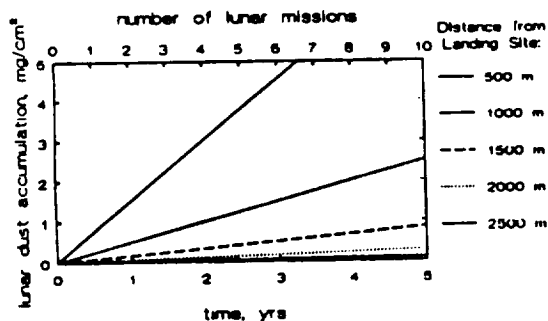
- COMPLETE FOR SDIO ENVIRONMENTS
- CONSIDERED A MAJOR SUCCESS, AND HAS BEEN EMBRACED BY LARGE COMMUNITY OF MILITARY SPACECRAFT DESIGNERS & ENGINEERS
- A VERSION CALLED ENVIRONMENTS WORKBENCH IS UNDER DEVELOPMENT FOR SPACE STATION DESIGNERS

• NEW NASA MISSIONS DEMAND NEW ENVIRONMENT AND EFFECTS MODULES AND VALIDATION THEREOF

- LUNAR/MARS BASES
- NEP/NTP

RWB-91Q.04.30

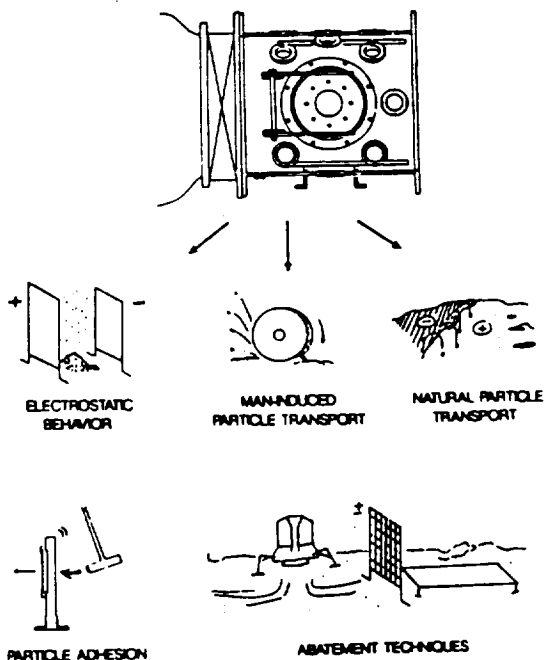
LUNAR ENVIRONMENTAL INTERACTIONS WITH POWER SYSTEMS

PREDICTED LUNAR DUST ACCUMULATION
AFTER MULTIPLE MISSIONS
WITH 26,800-N LAUNCH VEHICLE

DUST ACCUMULATION PREDICTED TO:

- OCCUR BY SEVERAL MECHANISMS
- BE SIGNIFICANT WITH TIME, DISTANCE
- DRAMATICALLY REDUCE PV PERFORMANCE
- REDUCE RADIATOR PERFORMANCE

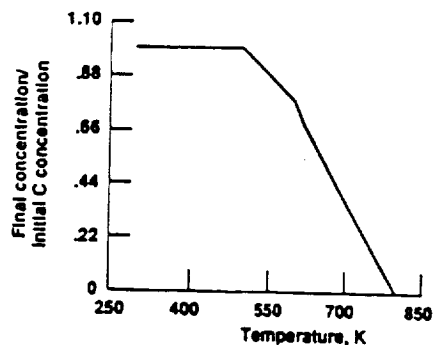
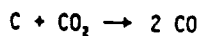
THEORETICAL APPROACH

LUNAR ENVIRONMENTAL
SIMULATION FACILITY

EXPERIMENTAL APPROACH

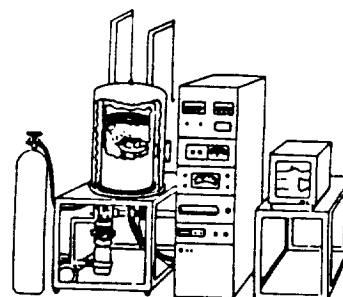
DURABILITY OF MARTIAN SURFACE POWER SYSTEMS

THEORETICAL PREDICTIONS



EXPERIMENTAL VERIFICATION

Martian Atmospheric Chemistry Simulator (MACS)

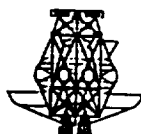
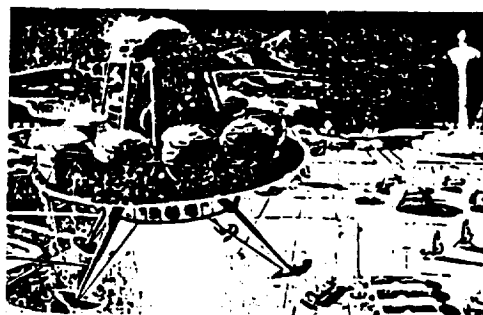


- DUST ACCUMULATION
- AEOLIAN EFFECTS
- CHEMICAL DEGRADATION
- COMPONENT TESTING

- THERMAL CYCLING
- RADIATION DAMAGE
- PASCHEN BREAKDOWN
- ABATEMENT TECHNIQUES

UTILITY POWER FOR SPACE EXPLORATION

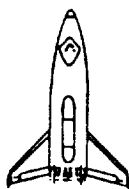
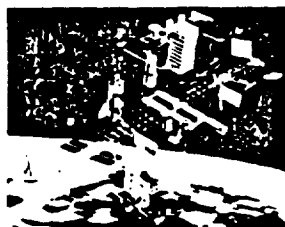
- COMBINES SPACECRAFT & TERRESTRIAL ATTRIBUTES
- SPACE INFRASTRUCTURE REQUIRES COMMONALITY WITH DIVERSITY
- REQUIREMENTS AND APPROACH NEED TO BE DEFINED
- SPACECRAFT DESIGNS INAPPROPRIATE



SBO TV



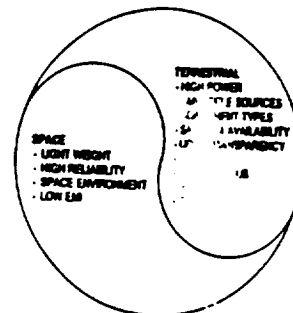
PLATFORM



SHUTTLE II



ALS



EXPLORATION MISSIONS

NEW SYSTEMS

- LUNAR/MARS BASE
- ADVANCED LAUNCH SYSTEMS
- SPACE STATIONS
- TRANSFER VEHICLES (CHEMICAL)
- ROVERS
- TRANSFER VEHICLES (NUCLEAR)

NEW TECHNOLOGIES

- NUCLEAR REACTOR
- SOLAR DYNAMIC
- CONVERSION
 - BRAYTON
 - STIRLING
 - RANKINE
- REGEN-FUEL CELL
- FLYWHEEL

CHANGED LOADS

- 1 kW TO >MW
- CONNECTABLE LOADS
 - DIVERSE (SOME LARGE) & > 100
 - >> GEN. CAPACITY
 - LOAD SCHEDULING
- SYSTEM INTERCONNECT
- MOTOR & ELECTRICAL ACTUATOR
 - HIGH REACTIVITY
 - HIGH PEAK POWER
 - REVERSE POWER FLOW

**FUTURE POWER SYSTEMS WILL BE VERY
DIFFERENT FROM TODAY'S SPACECRAFT SYSTEMS**

RWB-91Q.02.5

EXPLORATION MISSIONS

GENERIC REQUIREMENTS

- HIGH SAFETY & AVAILABILITY (MANNED SYSTEMS)
- FLEXIBILITY (GROWTH & EVOLVING MISSIONS)
- UNLIMITED POWER SYSTEM LIFE (POWER INTEGRAL TO SYSTEM)
- IN-SITU ASSEMBLY AND SERVICING
- USER TRANSPARENCY (MULTIPLE INDEPENDENT ACTIVITIES)

DEDICATED vs UTILITY POWER SYSTEMS

REQUIREMENTS

CHARACTERISTIC	DEDICATED	UTILITY
Source Capacity	1 -10 kW	kW - MW
Source Number	1 -2	Multiple
Growth	No	Yes
Lifetime	Fixed	Extendible
Repairable	No	Yes
Load/Source Cap.	~ 1	>>1
Physical Size	Small	Large
Flexibility	Loads fixed	Loads vary
Manned	No	Yes

APPROACH

DEDICATED

FOCUS ON MEETING

- MISSION SPECIFIC REQUIREMENTS
- ADAPT EXISTING SPACECRAFT BUS

UTILITY

• FOCUS ON MAJOR SYSTEM ELEMENTS

- GENERAL REQUIREMENTS
- FUNCTIONS
- MUTUAL COMPATIBILITY
- COMBINE MODULAR ELEMENTS
- INCLUDE REQUIREMENTS FOR
 - REPAIRS
 - USER TRANSPARENCY
 - EVOLUTIONARY DEVELOPMENT

UTILITY APPROACH INCREASES DDT&E COSTS
BUT BROADENS APPLICABILITY AND LOWERS LIFE CYCLE COSTS.

RWB-910.02.7

BASE R&T: SPACE ENERGY CONVERSION

POWER MANAGEMENT

SPACE UTILITY SYSTEMS AC versus DC

- SPACE SYSTEMS - BASED ON DC
- TERRESTRIAL & AIRCRAFT - BASED ON AC
 - HEAVY
 - HIGH FREQUENCY AC DEVELOPED TO REDUCE MASS
- SSF FREQUENCY SELECTION
 - EXTENSIVE TRADE STUDIES
 - DC AND 20 kHz AC TESTBEDS (25 kW)
 - TECHNOLOGY READINESS
 - SELECTED DC (FY91 BUDGET RESTRICTIONS)
 - LOWER DEVELOPMENT COST, LOWER PERFORMANCE
 - HIGHER TRANSPORTATION COSTS
- DATA BASE FOR SPACE EXPLORATION

AC versus DC POWER CONDITIONING

- AC TRADES UP-STREAM COMPLEXITY FOR DOWN-STREAM SIMPLICITY
 - e.g. INVERTER + TRANSFORMERS vs. DIRECT COUPLE + DC-DC CONVERTER
- DC ATTRACTIVE FOR SPACECRAFT POWER
 - DIRECT-COUPLED SOLAR ARRAY
 - SIMPLE DISTRIBUTION & LOAD STRUCTURE (DOWN STREAM)
- AC ATTRACTIVE FOR SPACE UTILITY
 - COMPLEX DISTRIBUTION
 - HIGH FANOUT

RWB-91Q.04.18

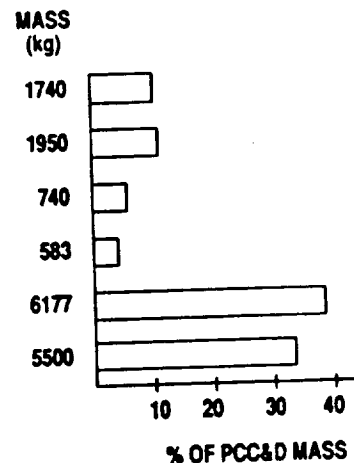
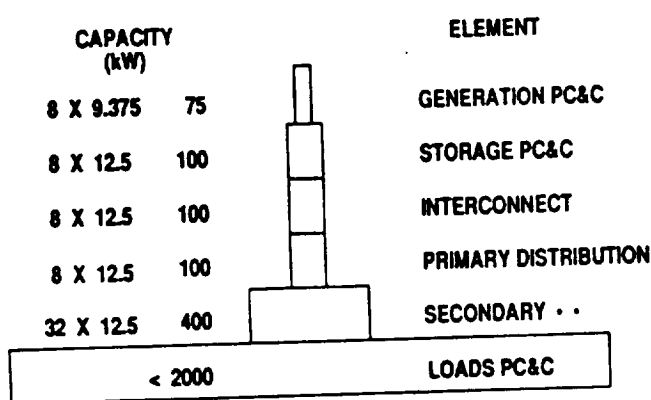


POWER TECHNOLOGY DIVISION



UTILITY POWER

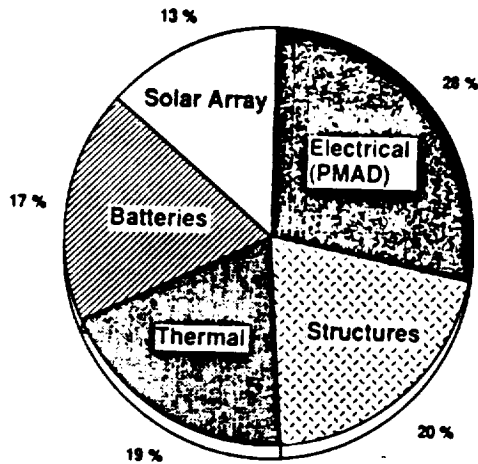
SUBSYSTEM CAPACITIES & MASSES (SSF EXAMPLE)



RWB-91Q.02.14

ADVANCED PMAD FOR GROWTH STATION

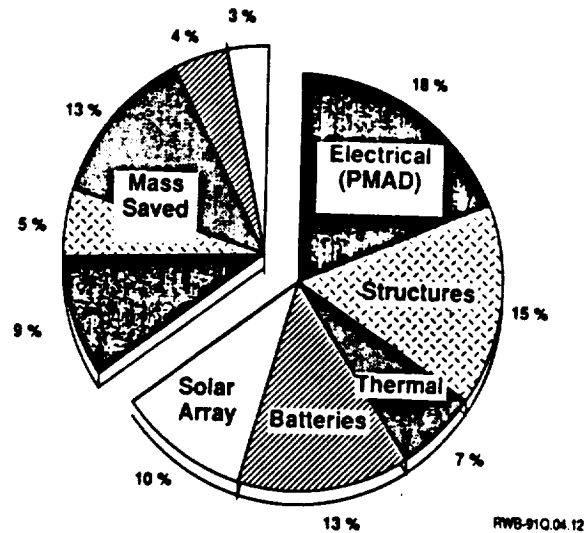
MASS DISTRIBUTION AND SAVINGS



PRESENT POWER SYSTEM MASSES

HIGH FREQUENCY AC AND HIGH TEMPERATURE PMAD COMPONENTS

- LIGHTER PMAD
- HIGHER EFFICIENCY
- REDUCED ARRAYS & BATTERIES
- REDUCED RADIATORS & THERMAL SYSTEMS



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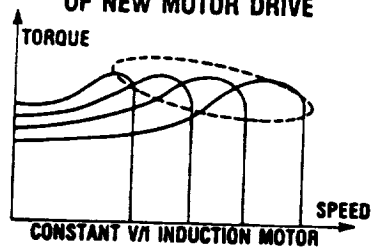
NASA
C-98-83987

POWER TECHNOLOGY DIVISION

NASA
Lewis Research Center

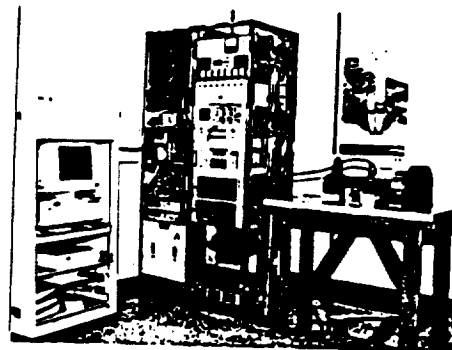
HIGH FREQUENCY LINK, INDUCTION MOTOR DRIVE SYSTEM

PRINCIPLES/BENEFITS OF NEW MOTOR DRIVE



- DEMO 5Hp INDUCTION MOTOR DRIVE
 - PULSE POPULATION MODULATION FROM HIGH FREQUENCY LINK
 - FIELD ORIENTED CONTROL
- MAX TORQUE AND EFFICIENCY AT ANY SPEED
- MINIMIZES STRESS ON ELECTRICAL COMPONENTS
- MINIMIZES EMI/EMC

MOTOR DRIVE TEST SET-UP



PAYOFFS FOR LAUNCH VEHICLES AND AIRCRAFT:

- OPERABILITY—LAUNCH ON DEMAND
- REDUCE MAN TESTS, COSTS
- ELIMINATE HYDRAULICS, APU'S, CARTS
- REDUCE WEIGHT, ENERGY

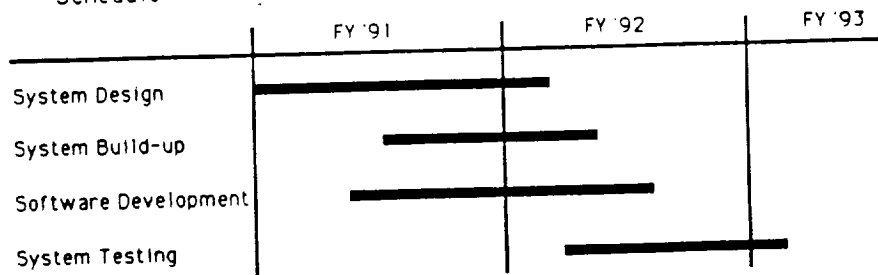
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POWER TECHNOLOGY DIVISION

LeRC IN-HOUSE EMA

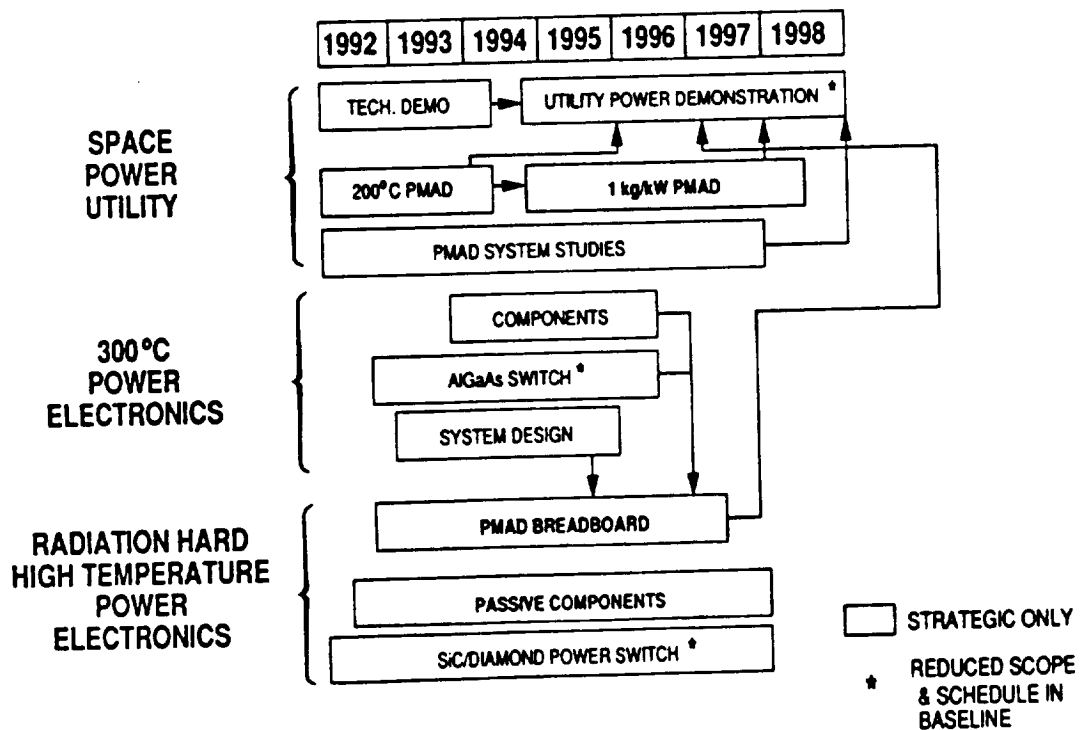
(ELV/ATLAS)

- Joint NASA-General Dynamics exchange program
- 20 Hp nominal, 30 Hp peak induction motor drive system
- BIT (Built-In-Test) capability
 - Phase voltage and current testing
- DSP Control scheme
- Optically coupled, closed loop field oriented control
- Schedule



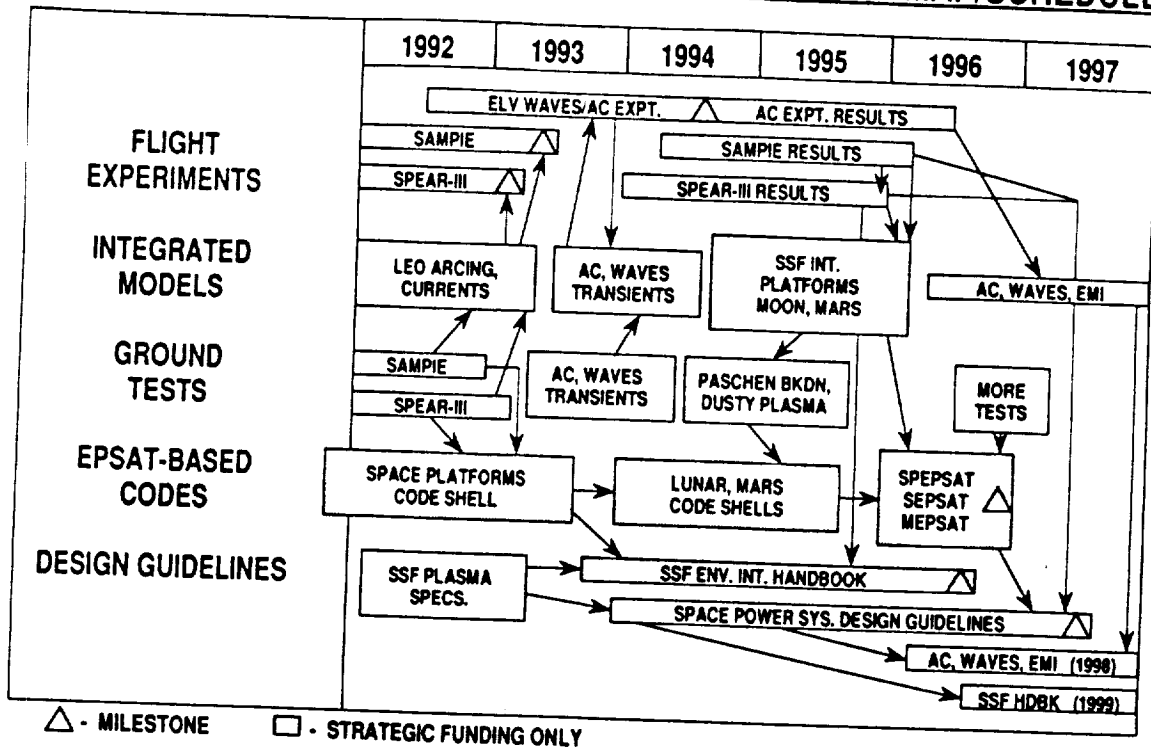
BASE R&T: SPACE ENERGY CONVERSION POWER MANAGEMENT

SPACE-UTILITY/HIGH TEMPERATURE PMAD ROADMAP/SCHEDULE



RWB-91Q.04.19

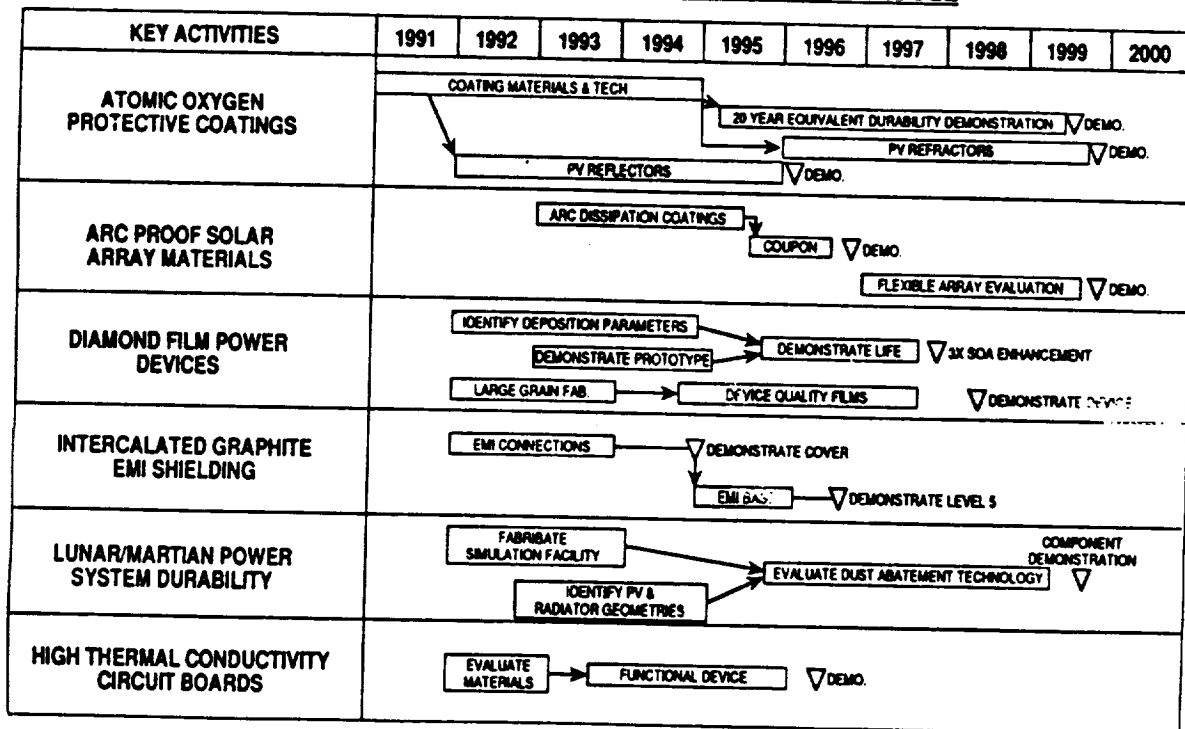
PMAD SPACE ENVIRONMENTAL INTERACTIONS ROADMAP/SCHEDULE



FB91-002.1

SPACE SCIENCE TECHNOLOGY
POWER MATERIALS TECHNOLOGY

POWER MATERIALS TECHNOLOGY ROADMAP/SCHEDULE



31-01210

OAET POWER INTEGRATION TECHNOLOGY

ROADMAP/SCHEDULE

R&T BASE POWER INTEGRATION TECHNOLOGY		1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
POWER SWITCH HYBRID	CURRENT	HYBRID SWITCH		SMART PROTOTYPE			SMART HYBRID MODULE				MONOLITHIC SMARTS
	AUGMENTED			SMART PROTOTYPE		SMART HYBRID MODULE			MONOLITHIC SMARTS		INTEGRATED SMART POLE
SYNCHRONOUS RECTIFICATION	CURRENT			PROTOTYPE		ADVANCED PROTOTYPE			SMART PROTOTYPE		
	AUGMENTED			PROTOTYPE		ADVANCED PROTOTYPE			SMART PROTOTYPE		INTEGRATED SMART SYNCH. RECT.

JUNE 26, 1991

POWER MANAGEMENT

ACCOMPLISHMENTS - TRANSFERRED TECHNOLOGY

POWER INTEGRATION

- ELECTRONIC SWITCHING (REMOTE POWER CONTROLLER) ADOPTED FOR CRAFT

ELECTRICAL COMPONENTS AND SYSTEMS

- DEVELOPED FIRST LARGE POWER TRANSISTOR (D60T) - NOW IN WIDE USE IN DoD AND INDUSTRY
- 150 VDC REMOTE POWER CONTROLLER ADOPTED FOR SSF
- "ROLL RING" ROTARY POWER TRANSFER DEVICE ADOPTED FOR SSF
- HIGH FREQUENCY PMAD ADOPTED FOR SSF (LATER CHANGED TO DC)
- PULSE DENSITY MODULATED DRIVE AND INDUCTION MOTORS ADOPTED FOR ALS TVC AND PRIME CANDIDATE FOR NLS ACTUATORS
- MOSFET CONTROLLED THYRISTOR (MCT) NOW IN PRODUCTION
- FIBER OPTIC CURRENT METER TO BE PRODUCED BY 3M FOR POWER INDUSTRY APPLICATION

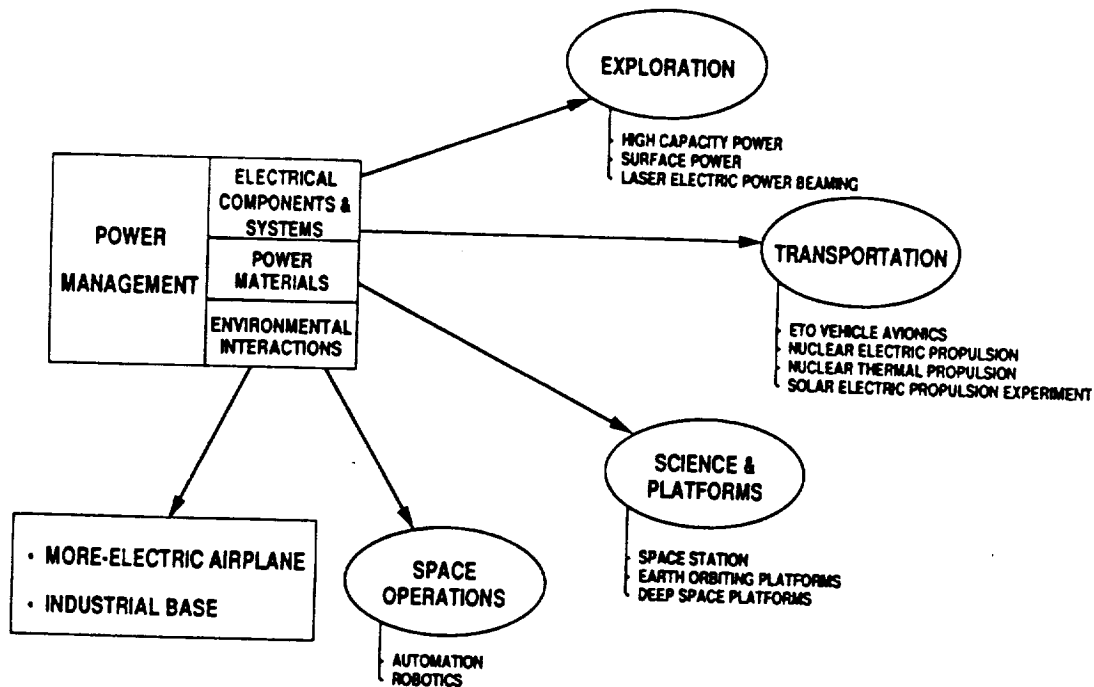
ENVIRONMENTAL INTERACTIONS

- NASCAP IN WIDE USE FOR DESIGN OF GEO SPACECRAFT
- EPSAT IN USE FOR SDIO MISSIONS
- SSF ARRAY DESIGNS BASED ON SAMPIE AND LARC TESTS
- REVISED "GROUNDING" FOR SSF

POWER MATERIALS

- ATOMIC OXYGEN PROTECTION COATING USED ON SSF ARRAYS
- COATING ALSO BEING EVALUATED FOR BEVERAGE INDUSTRY
- Z93 COATING USED ON SSF RADIATORS
- DIAMOND-LIKE FILMS TO BE USED FOR FACE SHIELDS, HELICOPTER WIND SHIELDS & EYE GLASSES

WIDE APPLICATION TO FOCUSED PROGRAMS



RWB-91Q.04.6

SUMMARY

- **TECHNICAL CHALLENGE:** FOR ALL MISSIONS, PMAD INTEGRATES POWER SUBSYSTEM WITH THE TOTAL SYSTEM AND SATISFY ITS REQUIREMENTS. NEW TECHNOLOGY IS REQUIRED TO:
 - MEET EMERGING NEEDS OF NEW MISSIONS: BASES, ROVERS, PLATFORMS, VEHICLES
 - REDUCE PMAD MASS AND COST (NOW 1/2 - 1/4 THOSE OF POWER SYSTEM)
 - INCREASE SYSTEM SAFETY, LIFE, FLEXIBILITY AND USABILITY
- **APPROACH:** MUST ADDRESS EXTREMELY COMPLEX SET OF ISSUES, MULTIPLE TECHNOLOGIES AND A MASSIVE COMMERCIAL INFRASTRUCTURE
 - FOUR INTERLINKED RESEARCH GROUPS WITH DIFFERENT SPECIALTIES
 - SYSTEM ANALYSIS TO IDENTIFY ISSUES AND QUANTIFY BENEFITS
 - COMMERCIAL DEVELOPMENT & MARKET SERVE AS PROGRAM AMPLIFIERS
- **PAYOFF:** IMPACTS ALL MISSIONS, EITHER ENABLING OR ENHANCING
 - SIGNIFICANTLY REDUCED MASS AND COST
 - GREATER SAFETY, RELIABILITY AND LIFETIME
 - FLEXIBLE AND USER FRIENDLY POWER SYSTEMS
 - CONFIDENT SYSTEM DEVELOPMENT
- **FUNDING AUGMENTATION** NEEDED TO ASSURE THAT ALL CRITICAL ISSUES ARE ADDRESSED AND TECHNOLOGY INFRASTRUCTURE IS AVAILABLE WHEN NEEDED
- **PMAD PROGRAM IMPACTS ALL FOCUS THRUSTS AND 12 THRUST ELEMENTS**
 - STRONG SYNERGISM WITH AERONAUTICS, DoD PROGRAMS AND COMMERCIAL APPLICATIONS

RWB-91Q.04.31

OAET

INTEGRATED TECHNOLOGY PLAN
EXTERNAL REVIEW
-JUNE 26, 1991-

BASE R & T PROGRAM
THERMAL MANAGEMENT
(506-41-51)

T. D. SWANSON

GODDARD SPACE FLIGHT CENTER

BASE R&T PROGRAM
SPACE ENERGY CONVERSION R&T

OAET

THERMAL MANAGEMENT

• OBJECTIVES

• PROGRAMATIC

DEVELOP ADVANCED ORBITAL AND
PLANETARY THERMAL CONTROL
TECHNOLOGIES WITH LOW MASS, HIGH
RELIABILITY, AND LONG LIFE

• TECHNICAL

HEAT PUMPS 7 KG/KW
RADIATOR MASS 1 - 4 KG/M2
CRYOGENIC HEAT PIPES 3X
POWER ELECTRONICS 1/20

• SCHEDULE

- 1992 DEMONSTRATE LIQUID SHEET
RADIATOR
- 1996 DEMONSTRATE 2X SOA IMPROVEMENT
IN CRYOGENIC HEAT PIPES
- 1996 DEMONSTRATE ADVANCED HEAT PUMPS
(3X SOA) SUITABLE FOR MICRO G
- 1997 COMPLETE INTEGRATED TEST FOR
POWER ELECTRONICS RADIATOR
- 1999 VALIDATE ANALYTICAL MODELS FOR
HEAT PUMPS AND HEAT PIPES

• RESOURCES

YEAR	CURRENT	STRATEGIC
• 1993	\$ 1.0M	\$ 1.1M
• 1994	\$ 1.1M	\$ 1.4M
• 1995	\$ 1.1M	\$ 1.7M
• 1996	\$ 1.2M	\$ 1.9M
• 1997	\$ 1.2M	\$ 2.3M
• 1998	\$ 1.3M	\$ 2.6M
• 1999	\$ 1.3M	\$ 3.0M

• PARTICIPANTS

• GODDARD SPACE FLIGHT CENTER

RESPONSIBILITY INCLUDES THERMAL CONTROL OF
INSTRUMENTATION, SENSORS, AND OTHER HEAT
DISSIPATING EQUIPMENT

• LEWIS RESEARCH CENTER

RESPONSIBILITY INCLUDES ADVANCED RADIATOR
CONCEPTS AND ADVANCED POWER ELECTRONICS
COOLING

PROGRAM SCOPE

OAET

THE THERMAL MANAGEMENT BASE R & T PROGRAM WILL SUPPORT FUTURE ORBITAL, DEEP SPACE, AND PLANETARY MISSIONS BY DEVELOPING A BROAD, GENERIC TECHNOLOGY BASE IN NEW THERMAL CONTROL SYSTEMS AND COMPONENTS.

CURRENT THERMAL MANAGEMENT SITUATION

OAET

THERMAL CONTROL TECHNOLOGY IS CURRENTLY EXPERIENCING A MAJOR GROWTH IN REQUIREMENTS. THIS IS DRIVEN BY MAJOR INCREASES IN SPACE-CRAFT:

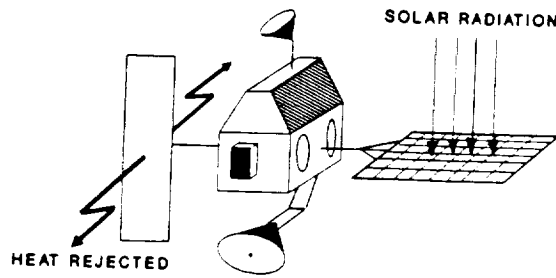
- PHYSICAL SIZE
- POWER LEVEL
- COMPLEXITY

EVOLUTION OF TECHNOLOGY FROM DISCRETE TO
CENTRAL THERMAL CONTROL

IMPLICATIONS INCLUDE:

- NOW ENABLING TECHNOLOGY (EOS PLATFORM)
- GREATER RISK; FAILURE NOT GRADUAL, MAY CAUSE LOSS OF SPACECRAFT

GROWTH IN SIZE

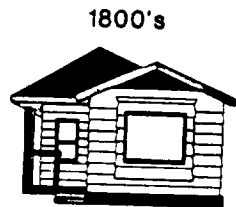


POWER IN =
HEAT REJECTED

<u>SUBSYSTEM</u>	<u>TRENDS</u>	<u>ISSUES</u>	<u>SOLUTIONS</u>
POWER	HIGHER LEVELS	GREATER SIZE AND WEIGHT	<ul style="list-style-type: none"> • HIGHER EFF. CELLS • NEW GENERATOR CONCEPTS
THERMAL	HIGHER POWER, TIGHTER LIMITS, LONGER DISTANCES	<ul style="list-style-type: none"> • SIZE/WEIGHT • CONTROL 	<ul style="list-style-type: none"> • HEAT PUMPS • TWO-PHASE BUS • NEW RADIATOR CONCEPTS

GROWTH IN COMPLEXITY

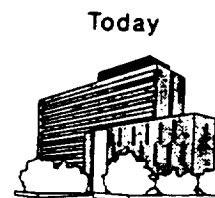
BUILDINGS/SPACECRAFT ANALOGY



Fireplace and Windows



Furnace and Windows



Central, multi-zone heating and cooling

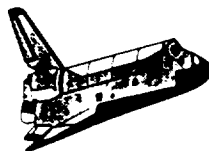


1960's and 1970's



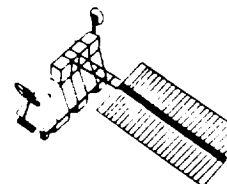
MLI and heaters

1980's

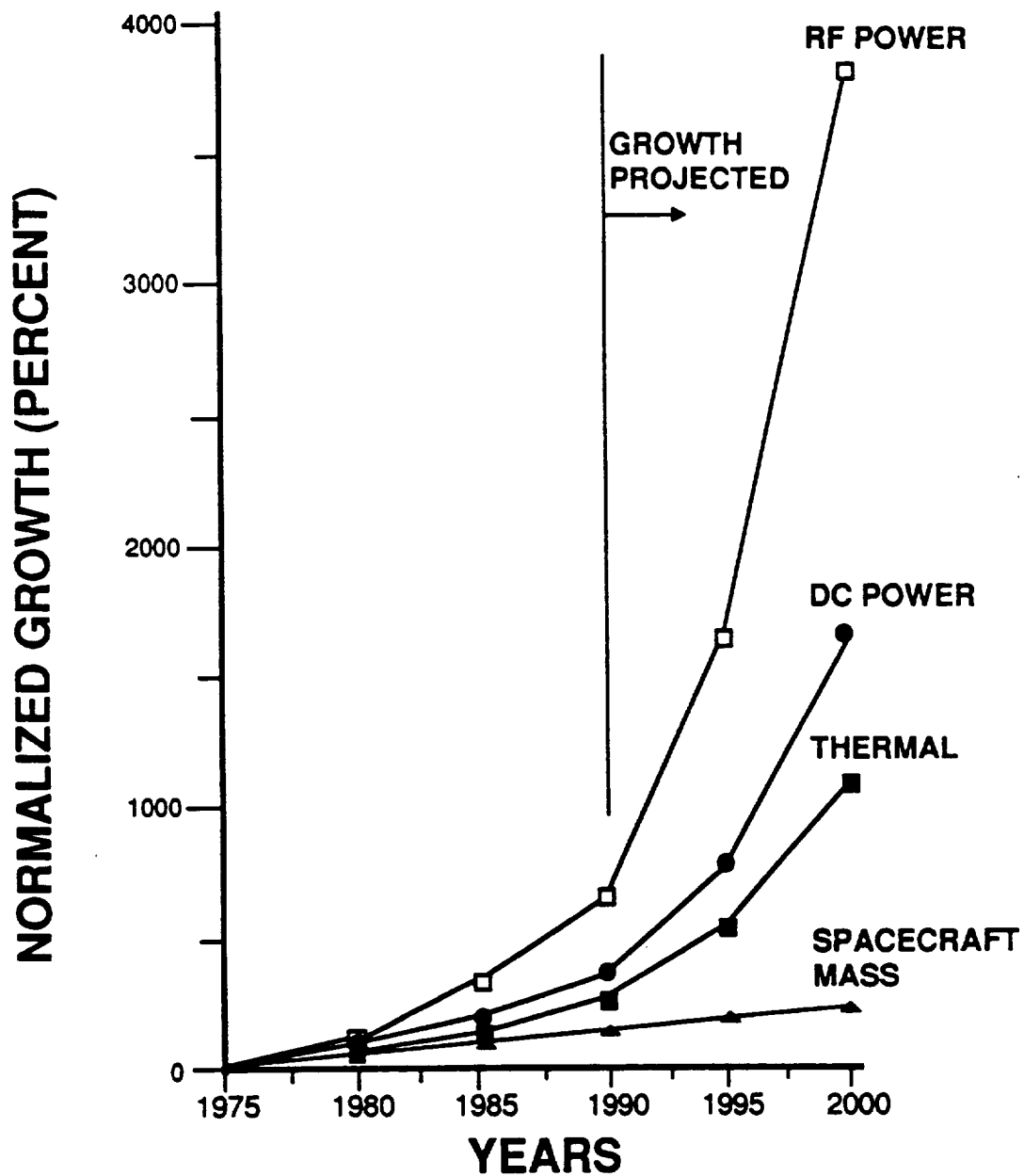


Pumped single phase and heat pipes

1990's

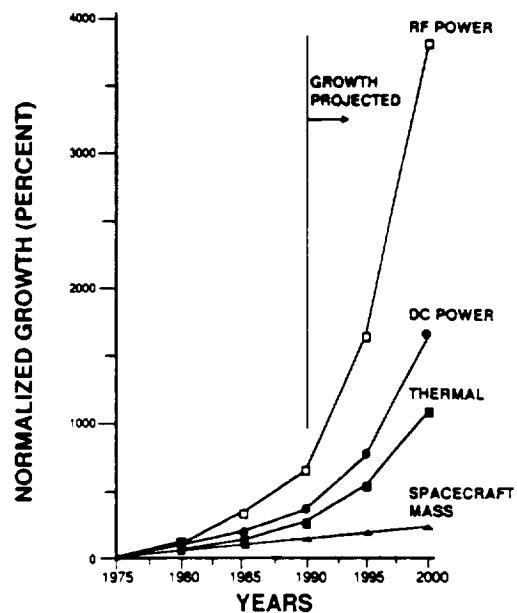


Two-phase central thermal bus



	BASELINE	CURRENT	PROJECTED
YEAR	1975	1990	2000
MASS (KG)	940	1300	1950
DC (W)	850	3750	15000
RF (W)	180	1350	7000
THERMAL DISSIPATION (W)	670	2400	8000

DOD PREDICTIONS



	BASLINE	CURRENT	PROJECTED
YEAR	1975	1990	2000
MASS (KG)	940	1300	1950
DC (W)	850	3750	15000
RF (W)	180	1350	7000
THERMAL DISSIPATION (W)	670	2400	8000

DOD PREDICTIONS

APPROACH

OAET

PROGRAMMATIC ELEMENTS FOR ACCOMPLISHING THIS EFFORT INCLUDE THE FOLLOWING:

- MISSION FOCUSED SYSTEMS LEVEL ANALYSIS STUDY TO IDENTIFY NEEDS
- MULTI-CENTER PARTICIPATION
- LEVERAGE WITH DOD, DOE AND OTHER NASA EFFORTS (SBIR, IN-STEP EXPERIMENTS, PROJECT SUPPORTED WORK)
- TRANSITION FROM OAET SUPPORT TO PROJECT SUPPORT AS TECHNOLOGY MATURES
- 10 TO 15 YEAR LEAD TIME NEEDED
- PURSUE MULTIPLE TECHNOLOGY OPTIONS (FOR STRATEGIC LEVEL OF FUNDING)

TECHNOLOGY NEEDS

OAET

ANALYSIS OF FUTURE MISSIONS, SUCH AS SECOND GENERATION EOS PLATFORMS, LUNAR BASE, MARS MISSION, AND CRAFT/CASSINI, INDICATE THE FOLLOWING FUTURE REQUIREMENTS:

- GREATER POWER LEVELS
- MORE HEAT LOAD SOURCES
- HEAT LOADS BURIED WITHIN BODY OF THE SPACECRAFT WITH NO VIEW TO SPACE
- CONFLICT BETWEEN RADIATOR VIEWS AND INSTRUMENT VIEWS
- GREATER TRANSPORT LENGTHS
- TIGHTER TEMPERATURE CONTROL
- INCREASED CRYOGENIC TEMPERATURE CONTROL
- HIGHER RELIABILITY
- LOWER WEIGHT

TECHNOLOGY OPTIONS

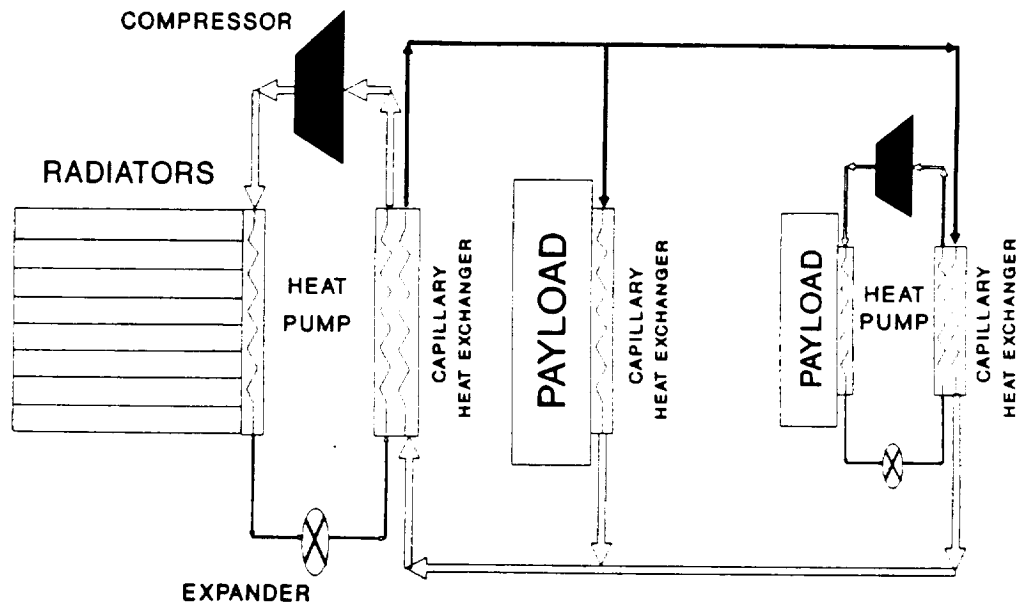
OAET

<u>TECHNOLOGY</u>	<u>HARDWARE/SOFTWARE NEEDED</u>
<ul style="list-style-type: none">• CENTRAL TWO-PHASE BUS	<ul style="list-style-type: none">• HEAT PUMPS• ANALYTICAL MODEL OF FLUIDS IN MICRO-GRAVITY• LONG LIFE MECHANICAL PUMPS FOR AMMONIA• PUMP CONTROLLER• UNDERSTANDING OF NON-CONDENSABLE GAS ISSUE• LIGHT WEIGHT MATERIALS
<ul style="list-style-type: none">• REDUCED RADIATOR AREA/WEIGHT	<ul style="list-style-type: none">• COMPOSITE RADIATORS• INNOVATIVE CONCEPTS• HEAT PUMPS• ELIMINATE NEED FOR EXTERNAL POWER ELECTRONICS RADIATOR• LIQUID METAL MICRO HEAT PIPE• DIRECT IMMERSION HEAT PIPE

HEAT PUMP TWO-PHASE BUS CONCEPT

-INCREASE REJECTION TEMPERATURE/COOL PAYLOAD-

OAET

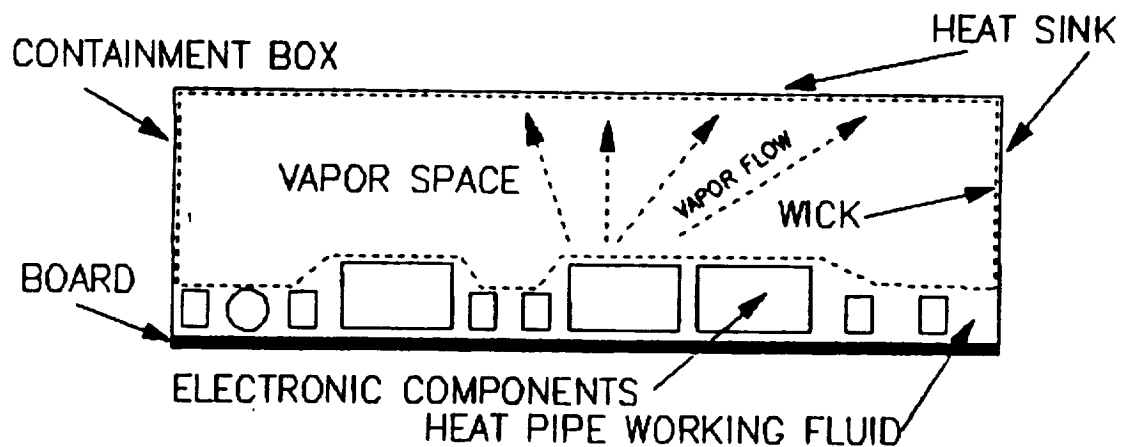


ANALYTICAL THERMAL DESIGN

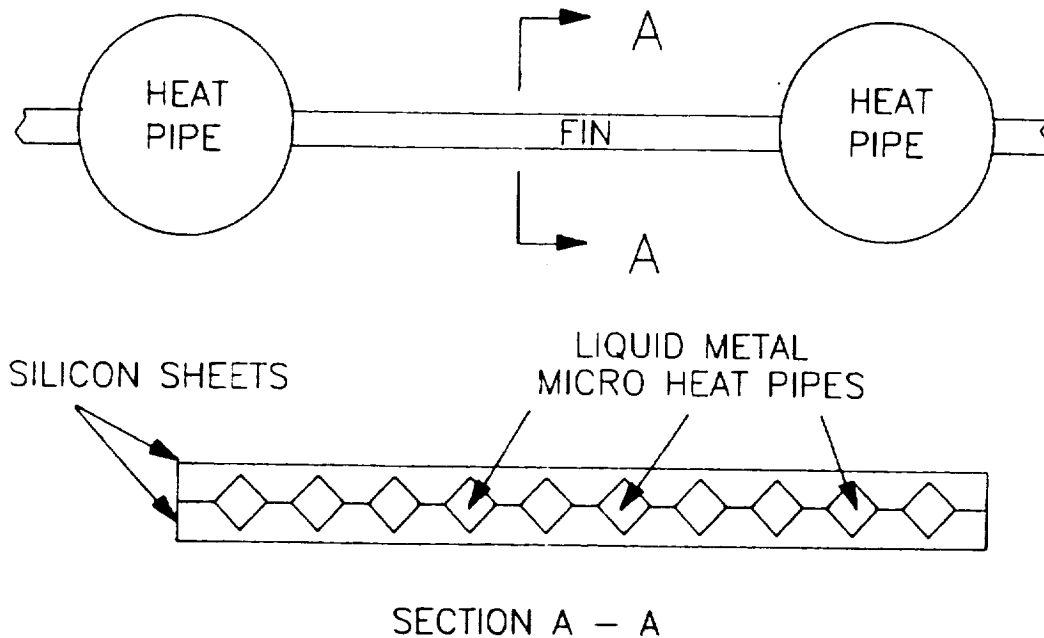
POWER TECHNOLOGY DIVISION

IWSI
Lewis Research Co.

DIRECT IMMERSION HEAT PIPE

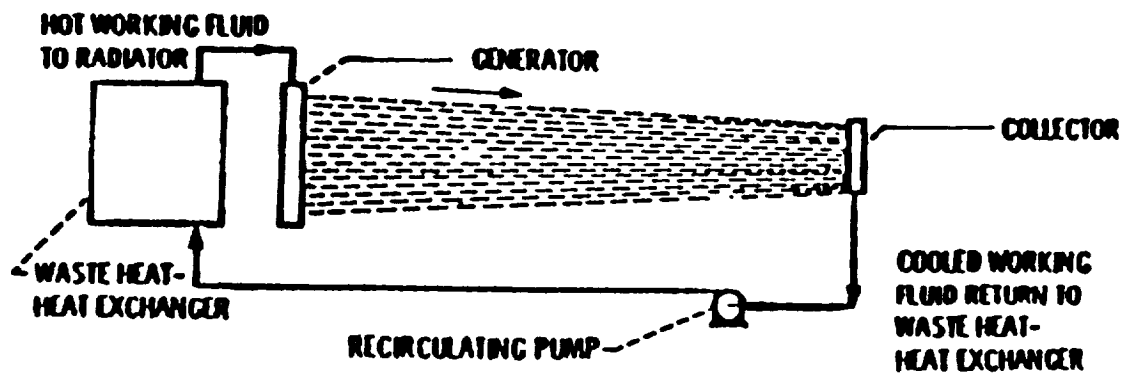


LIQUID METAL MICRO HEAT PIPE FINS



LIQUID DROPLET AND LIQUID SHEET RADIATOR

RADIATIVE "FINS" AND "HEAT PIPES" OF CONVENTIONAL RADIATORS
REPLACED BY STREAMS OF DROPLETS OR A LIQUID SHEET



TECHNOLOGY OPTIONS

(CONTINUED)

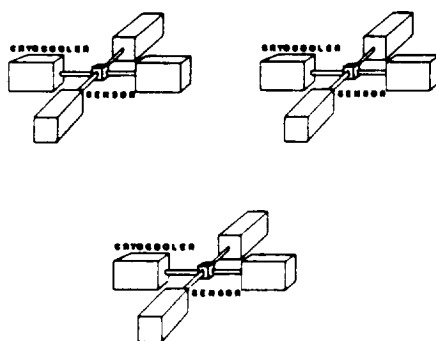
OAET

<u>TECHNOLOGY</u>	<u>HARDWARE/SOFTWARE NEEDED</u>
LOW TEMPERATURE THERMAL CONTROL	<ul style="list-style-type: none"> • CRYOGENIC HEAT PIPES • ANALYTICAL MODEL • CRYOGENIC TWO-PHASE BUS • THERMAL SWITCH
HIGH TEMPERATURE THERMAL CONTROL	<ul style="list-style-type: none"> • HIGH TEMPERATURE HEAT PIPES • ANALYTICAL MODEL • MATERIALS

CRYOGENIC HEAT PIPE APPLICATION

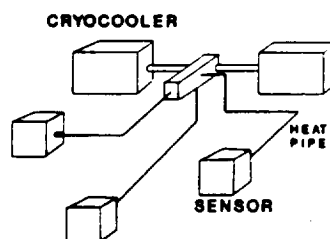
OAET

INDIVIDUALLY COOLED SENSORS



THREE SENSORS,
12 CRYOCOOLERS

CENTRAL BANK OF CRYOCOOLERS



THREE SENSORS,
2 TO 6 CRYOCOOLERS

TECHNOLOGY PAYOFF

OAET

- ENABLE CERTAIN MISSIONS
 - LUNAR BASE (LOW TEMPERATURE (<300 K) HEAT REJECTION)
 - ADVANCED ORBITAL PLATFORMS
- ENHANCE SCIENCE RETURN
 - LOWER WEIGHT FOR SUBSYSTEMS MEANS MORE WEIGHT AVAILABLE FOR SCIENCE PAYLOAD
 - LONGER LIFE/MORE RELIABLE THERMAL CONTROL WILL ALLOW LONGER MISSIONS
- ENABLE LARGER/MORE COMPLEX COMMERCIAL SATELLITES

STATE OF THE ART VS. GOALS

OAET

<u>TECHNOLOGY</u>	<u>STATE OF THE ART</u>	<u>GOAL</u>
HEAT PUMP	24 KG/KW	8 KG/KW
CRYO HEAT PIPE	10 W-m • 70 K	20 W-m • 70 K
LIGHTWEIGHT RADIATOR	9 KG/M2	1-4 KG/M2
ANALYTICAL MODELS FOR ENGINEERING PARAMETERS	N/A	VERIFIED BY MICRO-GRAVITY DATA
POWER ELECTRONICS RADIATOR	6 M2/KW	0.3 M2/KW
MECHANICAL PUMP	500 HOURS LIFE	80,000 HOURS LIFE

PROGRAM DESCRIPTION -RECENT ACCOMPLISHMENTS-

OAET

- OXYGEN AND NITROGEN CRYOGENIC HEAT PIPES
-FABRICATED AND TESTED, GOOD CORRELATION TO MODEL
- CRYOGENIC HEAT PIPE FLIGHT EXPERIMENT
-UNDERGOING PERFORMANCE TESTING, OCTOBER 1992 MANIFEST, JOINT EXPERIMENT WITH AIR FORCE (WRIGHT LABORATORY)
- HEAT PUMPS
-COMPLETED SYSTEM LEVEL STUDY, INITIATED COMPONENT LEVEL CONCEPTUAL DESIGN AND SPECIFICATION (LEVERAGED EFFORT WITH NIST)
- LIGHTWEIGHT MATERIALS
-COMPLETED SOA SURVEY, IDENTIFIED SEVERAL PROMISING CANDIDATES
- TWO-PHASE LOOPS
-INITIATED INNOVATIVE CONTROLLER STUDY AND TEST

PROGRAM DESCRIPTION -CURRENT AND STRATEGIC-

OAET

<u>TECHNOLOGY</u>	<u>ESTONE</u>	<u>SCHEDULE</u>
HEAT PUMPS	<ul style="list-style-type: none"> • DEVELOP TWO (<i>ONE</i>) BASIC DESIGN CONCEPTS • 3X SOA (<i>2X SOA</i>) IMPROVEMENT SPECIFIC WEIGHT • DESIGN FLIGHT EXPERIMENT 	<ul style="list-style-type: none"> • 1994 • 1996/ 1997 • 1999/ 2001
CRYOGENIC HEAT PIPES	<ul style="list-style-type: none"> • 50% (<i>35%</i>) IMPROVEMENT OVER SOA • DESIGN FLIGHT EXPERIMENT 	<ul style="list-style-type: none"> • 1995 • 1998
LIGHTWEIGHT RADIATORS	<ul style="list-style-type: none"> • IDENTIFY INNOVATIVE CONCEPTS • <i>CONSTRUCT MICRO HEAT PIPE FINS</i> • DEMONSTRATE 1-4 KG/M2 (<i>3-5 KG/M2</i>) RADIATOR 	<ul style="list-style-type: none"> • 1994 • 1995 • 1996

NOTE: ITALICS REFERS TO REDUCTION IN SCOPE/PERFORMANCE IF STRATEGIC FUNDING LEVEL IS NOT APPROVED

PROGRAM DESCRIPTION-CONTINUED

-CURRENT AND STRATEGIC-

<u>OAET</u>		
TECHNOLOGY	MILESTONES	SCHEDULE
POWER ELECTRONIC THERMAL CONTROL	• DEVELOP INNOVATIVE CONCEPTS	• 1993
	• 20:1 REDUCTION IN SIZE AND WEIGHT OF RADIATOR	• 1997
CRYOGENIC TWO- PHASE THERMAL BUS	• DESIGN CONCEPT	• 1995/ 1997
	• GROUND TEST	• 1998/ 2000
CODE VALIDATION	• WATER HEAT PIPE	• 1994/ 1997
	• LIQUID METAL HEAT PIPE	• 1996/ 1997
LIGHTWEIGHT MATERIALS	• 35% (20%) REDUCTION IN WEIGHT OF COMPONENTS	• 1997
ANALYTICAL MODEL	• CRYOGENIC HEAT PIPES	• 1996/1998
	• HEAT PUMPS	• 1999/2002

RESOURCE REQUIREMENTS

(\$ M)

<u>OAET</u>							
	<u>1991</u>	<u>1992</u>	<u>1993</u>	<u>1994</u>	<u>1995</u>	<u>1996</u>	<u>1997</u>
CURRENT	0.7	1.0	1.0	1.1	1.1	1.2	1.2
3X	0.7	1.0	1.1	1.4	1.7	1.9	2.3
STRATEGIC	0.7	1.0	1.1	1.4	1.7	1.9	2.3

RELATIONSHIP OF R & T BASE TO FOCUSED PROGRAM

OAET

FOCUSED PROGRAM ENHANCES BASE PROGRAM BY;

- PROVIDING MORE TECHNICAL OPTIONS FOR A GIVEN COMPONENT
- PROVIDING MORE SPECIFIC DESIGN AND ANALYSIS OF ISSUES FOR A GIVEN MISSION CLASS
- IMPROVING PERFORMANCE MARGIN
- ACCELERATING DEVELOPMENT SCHEDULE

RELATED TECHNOLOGY EFFORTS

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- EOS AND SPACE STATION PROJECTS
 - 40 C TWO-PHASE THERMAL BUS CONCEPTS
- IN-STEP
 - GREGORIG GROOVE HEAT EXCHANGER
 - LIQUID MOTION IN A TANK
- SBIR
 - MECHANICAL/CHEMICAL HEAT PUMP
 - SINTERED WICK CRYOGENIC HEAT PIPE
 - LONG LIFE MECHANICAL PUMP
 - COMPOSITE RADIATOR

AIR FORCE

- JOINT CRYOGENIC HEAT PIPE EXPERIMENT WITH NASA/GSFC
- HIGH TEMPERATURE HEAT PIPE
- ANALYTICAL MODEL FOR HEAT PIPES
- CAPILLARY PUMPED LOOPS

DOE

- ADVANCED HEAT ENGINES (STIRLING, ABSORPTION)

-SUMMARY-
R&T BASE: THERMAL MANAGEMENT

OAET

- TECHNICAL CHALLENGES: MICRO G PERFORMANCE, COST, LIFETIME
- APPROACH: FOCUS ON HEAT PUMPS, CRYOGENIC HEAT PIPES, INNOVATIVE RADIATORS, 20:1 REDUCTION FOR POWER ELECTRONICS RADIATOR, AND ANALYTICAL MODELS
- PAYOFF: ENABLE LUNAR BASE (300 K WASTE HEAT REJECTION), MAJOR IMPROVEMENT IN SENSOR COOLING, 50% OR MORE REDUCTION IN RADIATOR SIZE AND SPECIFIC MASS, AND BETTER ANALYTICAL MODELS
- AUGMENTATION RATIONALE: EXPAND BASE PROGRAM TO INCLUDE MULTIPLE OPTIONS, ADDRESS PROBLEMS NOT ADDRESSED IN BASE
- RELATIONSHIP TO OTHER PROGRAMS: BASE PROGRAM PROVIDES GENERIC FOUNDATION FOR MORE MISSION SPECIFIC FOCUSED EFFORT, SIGNIFICANT INTERACTION WITH AIR FORCE
- TECHNOLOGY CONTRIBUTIONS: CODE R FUNDED CAPILLARY PUMPED LOOP TECHNOLOGY NOW BASELINED FOR EOS PLATFORM - ENABLING TO THIS MISSION



SPACE NUCLEAR POWER (SP-100)

BY

R. J. SOVIE
DEPUTY CHIEF, POWER TECHNOLOGY DIVISION
NASA LEWIS RESEARCH CENTER

ITP EXTERNAL REVIEW

JUNE 27 1991



WHAT WE WILL DISCUSS

- OBJECTIVES/BENEFITS
- SP-100 BACKGROUND
- SCALING
- SP-100 GROUND ENGINEERING SYSTEM STORY
 - TECHNICAL CONTENT
 - PROGRAMMATICS
 - SP-100 REVIEW GROUP
 - PRESENT SCHEDULE
- TECHNICAL PROGRESS
- CONCLUDING REMARKS

**Space Nuclear Power****OBJECTIVES**• **Programmatic**

Develop and Validate Technologies for Safe and Reliable Nuclear Power Systems to Support Lunar Outpost and Mars Exploration Missions

• **Technical**

Power Level - 100 + kilowatts (nominal)
 Specific Mass - 30 - 50 kilograms per kilowatt
 Operations - Space- and Surface basable
 Life Time - 7 years at full power

SCHEDULE

- 1993 Thermoelectric Cell Fabricated and Tested in Relevant Thermal Environment
- 1994 NAT Fuel Pins Fabricated & In Storage
- 1995 Restart Nuclear Assembly Test Site
- 1996 Thermoelectric Converter/Electromagnetic Pump Subsystem Performance Testing Complete
- 2001 Complete Flight-Like Integrated Assembly Test and Nuclear Assembly Test for Lunar Outpost Nuclear Power Systems

RESOURCES***CURRENT**

- 1991 \$ 10.0 M
- 1992 \$ 20.0 M
- 1993 \$ 25.0 M
- 1994 \$ 25.0 M
- 1995 \$ 20.0 M
- 1996 \$ 20.0 M
- 1997 \$ 20.9 M

STRATEGIC/3X

- 1991 \$ 10.0 M
- 1992 \$ 20.0 M
- 1993 \$ 25.0 M
- 1994 \$ 25.0 M
- 1995 \$ 26.0 M
- 1996 \$ 27.0 M
- 1997 \$ 28.0 M

* Note: This Element Provides NASA's Contribution To The Ongoing NASA, DoD, DoE, SP-100 Program. Resources Shown are NASA's Contribution Only.

PARTICIPANTS

- **Jet Propulsion Laboratory**
Lead for SP-100 Ground Engineering System Project, Responsible for Component Technologies, Project Management
- **Lewis Research Center**
Space Subsystems, Materials
- **Los Alamos National Laboratory**
Lead for Reactor Systems/Fuel Development
- **Contractors**
General Electric

ITP RJ591-002.12



SPACE NUCLEAR POWER

SP-100

• **SP-100**

- NATIONAL PROGRAM
- DOE/NASA/DOD

TO DEVELOP SPACE REACTOR POWER SYSTEMS AT THE
10 kWe to 1 MWe POWER LEVELS FOR USE IN FUTURE
MILITARY AND CIVILIAN SPACE MISSIONS

ADVANCED TECHNOLOGY GOALS

		W/kg		
		<u>LEO</u>	<u>MARS</u>	<u>LUNAR</u>
PHOTOVOLTAICS	- 300 W/kg ARRAYS	16	NA	NA
BATTERIES	- 100 W-hr/kg			
REGEN. FUEL CELLS	- 1000 W-hr/kg		8	3
ADVANCED SOLAR DYNAMICS		16 < AREA	8	3
NUCLEAR REACTOR POWER SYSTEMS		25 - 40	← 25 - 65 →	
ROVERS, VEHICLES			← 5 - 10 →	



SURFACE POWER SYSTEM MASS DRIVERS

SPACE STATION

~ 60 MIN. LIGHT/30 MIN. DARK

LUNAR

~ 14 DAY DAY/NIGHT CYCLE

MARS

~ 12 HR DAY/NIGHT CYCLE

STORAGE

BATTERIES



REGENERATIVE FUEL CELLS

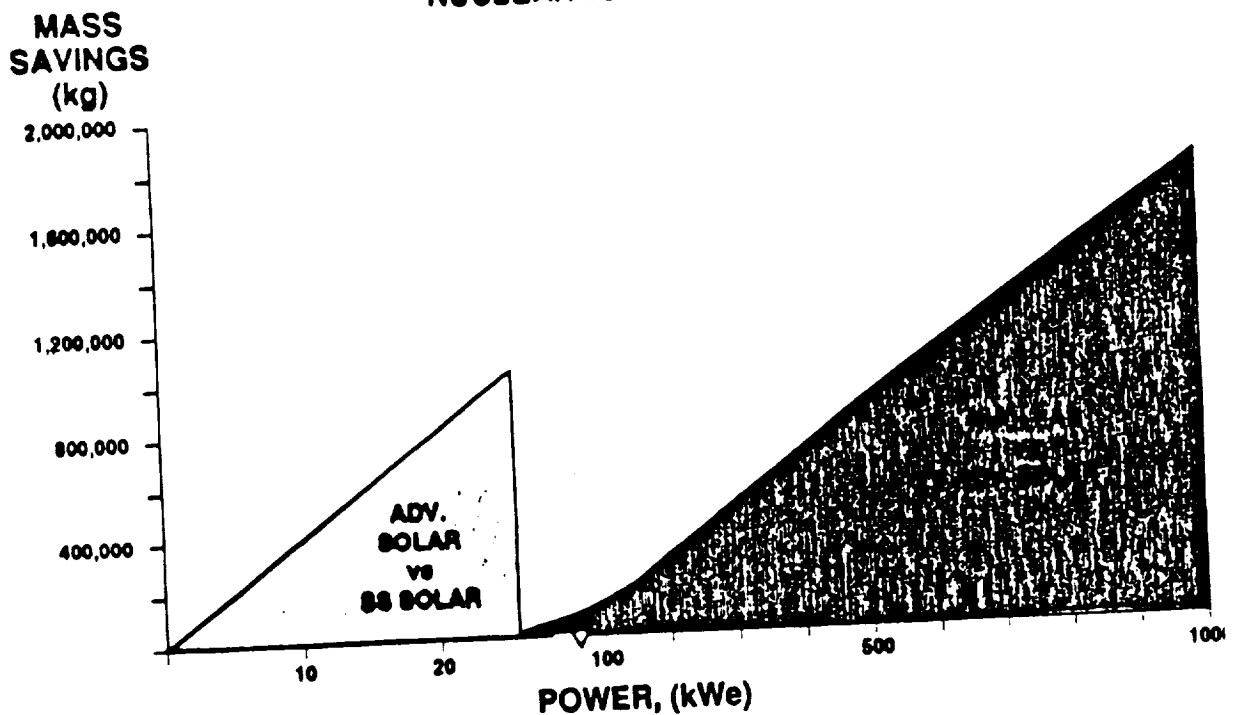


NUCLEAR



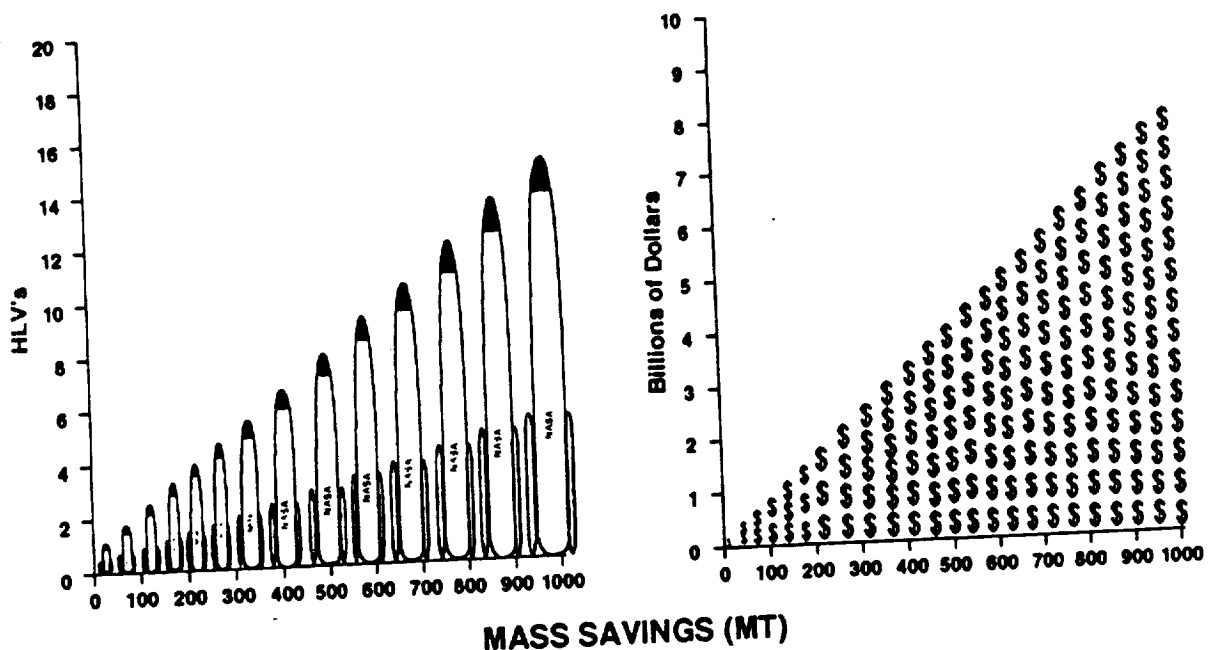
MASS SAVINGS IN LEO

ADV. SOLAR vs SPACE STATION SOLAR
NUCLEAR vs ADV. SOLAR



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MASS SAVINGS BENEFITS





SPACE NUCLEAR POWER SP-100

PROVIDES TECHNOLOGY FOR:

SPACE EXPLORATION

LUNAR, MARS SURFACE POWER

NEP PRECURSOR MISSIONS

SCIENCE

1 - 100 kWe NEP

TRANSPORTATION

1 - 40 MWe NEP CARGO, MANNED, & MARS TRANSFER VEHICLES



SPACE NUCLEAR POWER SP-100 KEY REQUIREMENTS

- SCALABLE: 10's TO 100's OF kWe
- LIFETIME: 7 YEARS FULL POWER - 10 YEAR LIFE (15)
- SAFE FOR ALL MISSION PHASES
- RADIATION SHIELDED TO PROTECT PAYLOAD
- SURVIVABLE
- SPACE SHUTTLE AND ELV COMPATIBLE
- ~ 25 W/kg AT 100 kWe (80 W/kg)



SP-100 BACKGROUND

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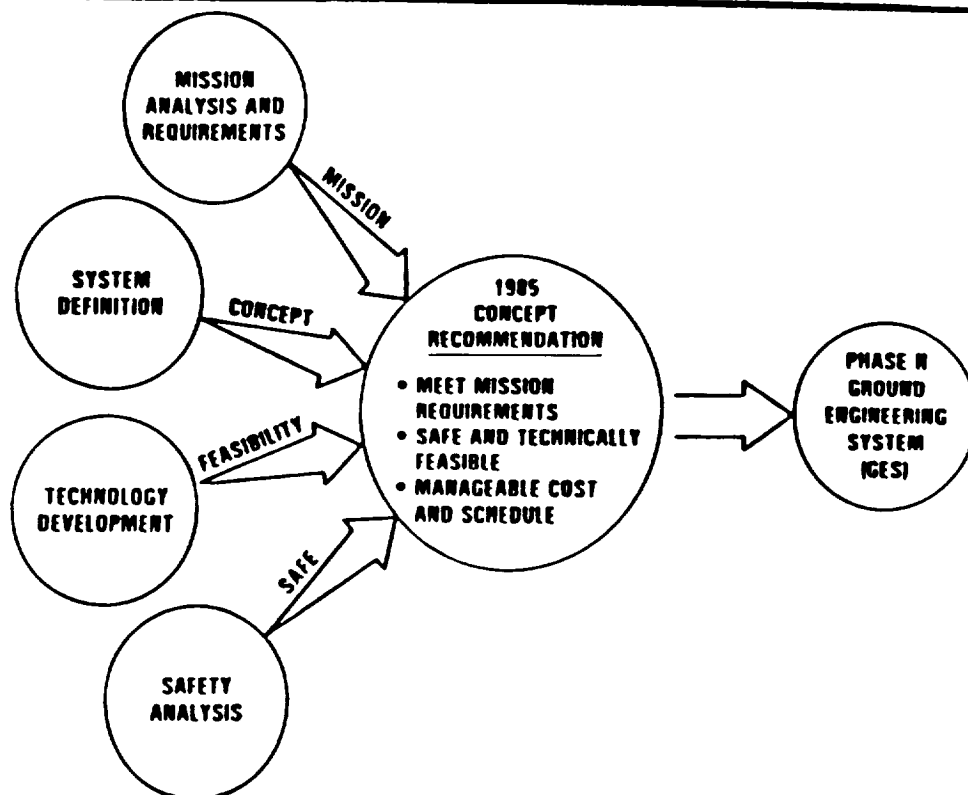
SP-100

PHASE I - CONCEPT SELECTION - 1983

PHASE II - TECHNOLOGY DEVELOPMENT AND VALIDATION

PHASE III - FLIGHT DEMONSTRATION (FSQ)

RJS-910045



NASA

SP-100 PHASE I

- 50 ORIGINAL CONCEPTS
- 4 FINAL CONTENDERS
 - LIQUID METAL COOLED REACTOR (LMR)
 - THERMOELECTRICS
 - BRAYTON
 - STIRLING
 - IN-CORE THERMIONICS SYSTEM

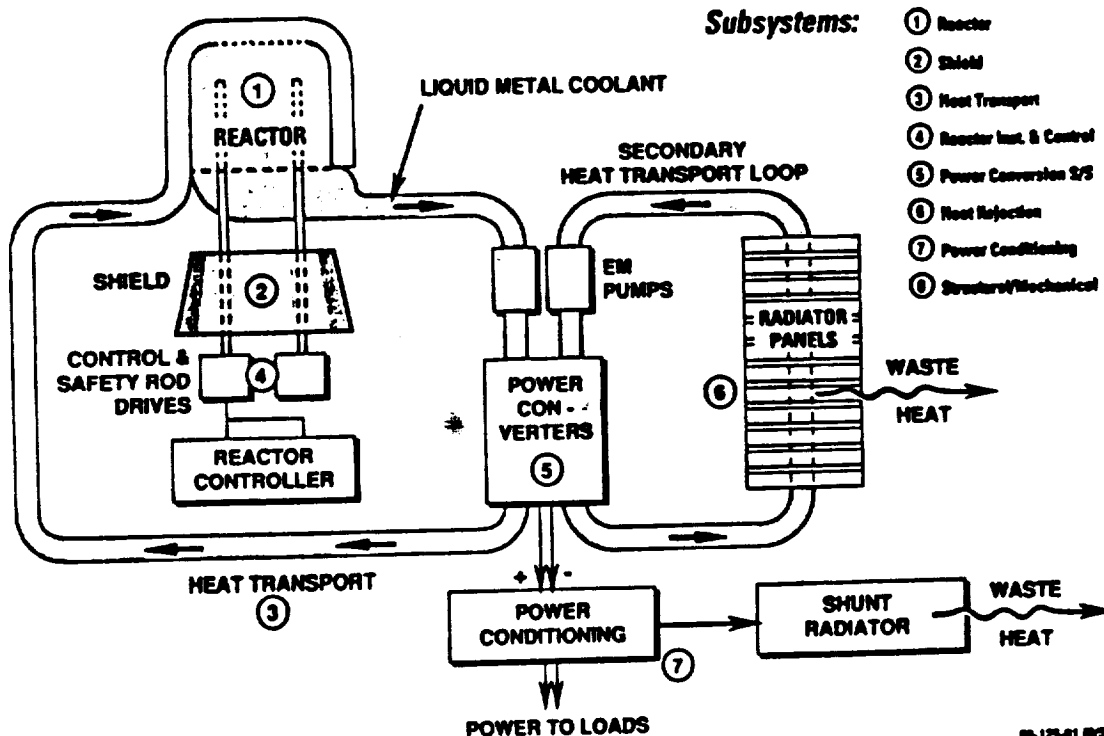


AT END OF PHASE I

- **SP-100 GROUND ENGINEERING SYSTEM**
 - LITHIUM COOLED REACTOR
 - TE CONVERSION
 - UN FUEL PWC-11 CLAD
 - 300 kWe → 100 kWe
- **ADVANCED TECHNOLOGY PROGRAM (CSTI - HIGH CAPACITY POWER)**
 - ADVANCED STATIC CONVERSION
 - DYNAMIC CONVERSION
 - RADIATORS
 - GROWTH
 - FALLBACK POSITIONS
- **THERMIONICS TECHNOLOGY PROGRAM**
 - ADDRESS UNRESOLVED FEASIBILITY ISSUES

RJS-910.04.9

Simplified System Diagram



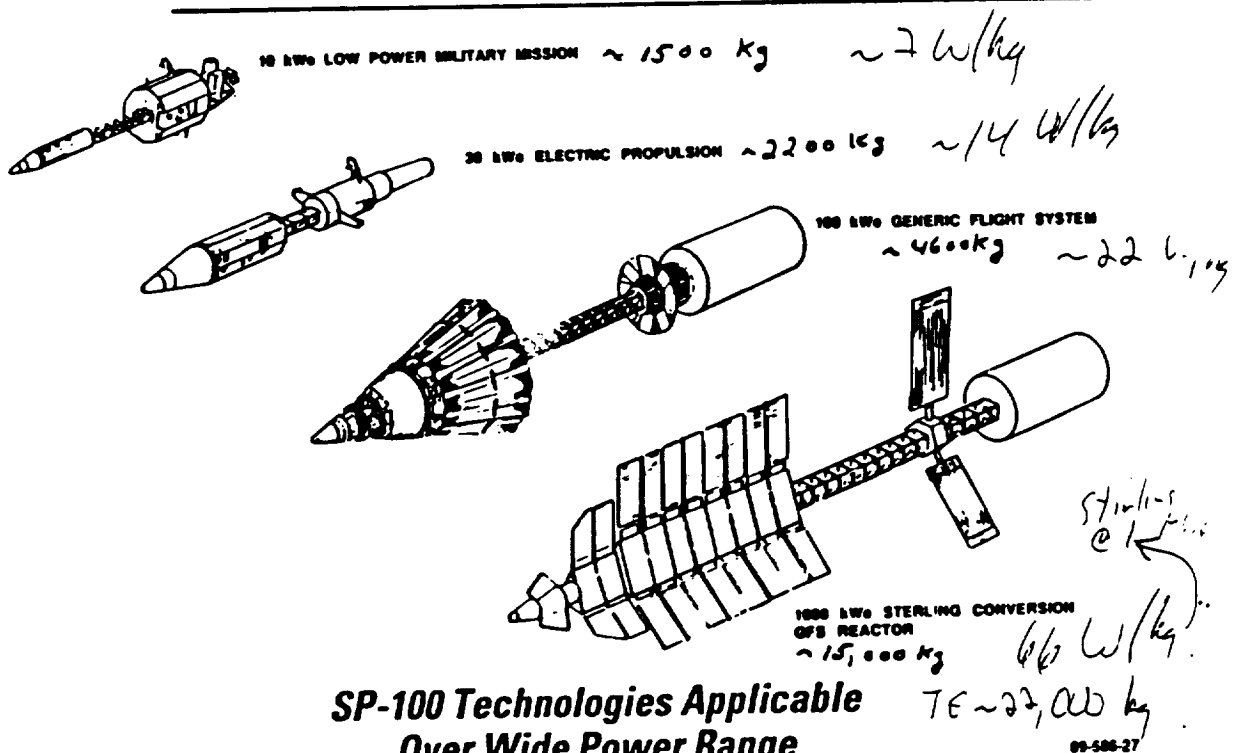
GS-125-01 (R7)



SCALING

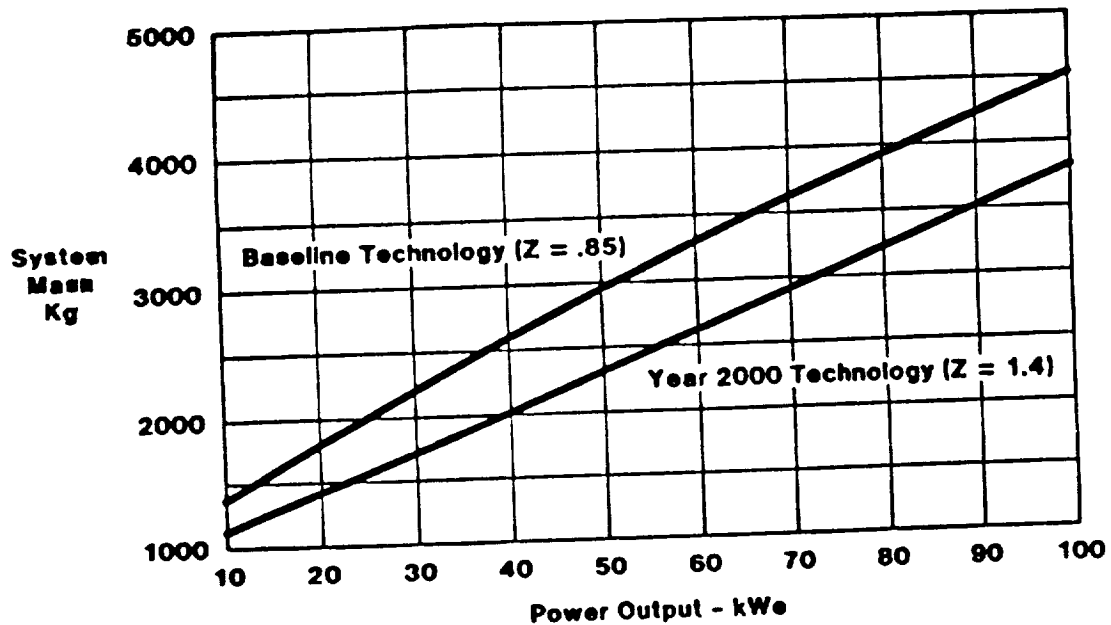
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Design Scalability





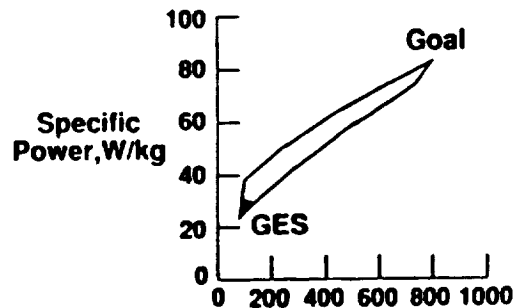
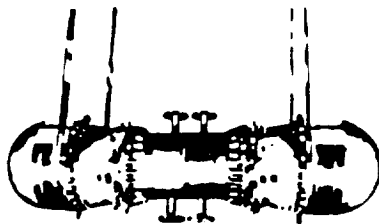
MASS SENSITIVITY TO T/E TECHNOLOGY STATUS



POWER TECHNOLOGY DIVISION

SPACE NUCLEAR POWER

High Capacity Power



- Free piston Stirling converters
- Advanced thermal management
- Power management & distribution
- Environmental interactions
- Thermoelectrics
- Materials development

CS-95-10001

AEROSPACE TECHNOLOGY DIRECTORATE



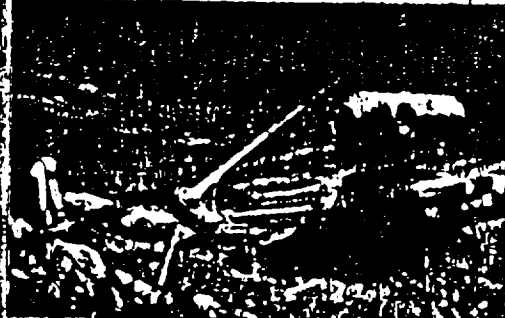
SP-100

NASA

Space Research Center

SMALL REACTORS FOR PLANETARY EXPLORATION

- ASSES USE OF SMALL REACTOR POWER SYSTEMS FOR NASA PLANETARY EXPLORATION MISSIONS
- 1-35 KW
- CASSINI REFERENCE MISSION



- 1 KW REACTOR FOR SCIENCE
- ALTERNATIVE FOR RTG
- TRIP TIME INCREASE ABOUT 1 YEAR
- 25 KW REACTOR FOR ELECTRIC PROPULSION & SCIENCE
- EQUAL OR REDUCED TRIP TIME
- ENHANCED SCIENCE
- INCREASED LAUNCH WINDOWS
- SP-100 TECHNOLOGY ATTRACTIVE FOR SMALL REACTOR

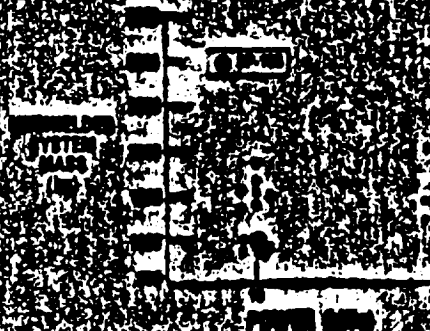


SP-100

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Space Research Center

SP-100 TECHNOLOGY ATTRACTIVE FOR LOW POWER REQUIREMENTS



- WIDE VARIETY OF ALTERNATIVE TECHNOLOGY CONCEPTS STUDIED
- SP-100 TECHNOLOGY AMONG THE MOST ATTRACTIVE
- REACTOR MASS IS SMALL FRACTION OF TOTAL SYSTEM



- SMALL REACTOR CAN PROVIDE AGENCY WITH ALTERNATIVE TO RTG's
- TECHNOLOGY IN NATIONAL SP-100 PROGRAM DIRECTLY APPLICABLE TO LOW POWER NEEDS

SP-100



NASA

SP-100 APPLICABILITY TO LARGE SCALE NEP 5 - 50 MWe

RJS91-003.11



NASA

MAJOR PARAMETERS CONSIDERED AND APPROACH USED

POWER RANGE CONSIDERED:	200 kWt TO 200 MWt
REACTOR LIFETIME:	10 YEAR BASELINE; LONGER LIFETIMES ARE FEASIBLE
FUEL/BURNUP:	UN / ≤ 10 ATOM %
COOLANT:	LITHIUM OR OTHER LIQUID METAL FOR PRIMARY HEAT TRANSPORT; - 1350K SECONDARY LOOP CAN BE LIQUID METAL, GAS, HEAT PIPES OR TBD
STRUCTURES:	REFRACTORY METAL; CAN USE HIGH TEMPERATURE ALLOYS SUCH AS 617 DEPENDING ON MISSION AND EXTERNAL ATMOSPHERE

RJS91-003.8



NASA

COROPT-S CODE CAPABILITIES

- o SP-100 NUCLEAR SUBSYSTEMS OPTIMIZATION CODE
- o USES FIRST PRINCIPLES TO SIZE REACTOR, SHIELD, PRIMARY HEAT TRANSPORT SYSTEM AND REACTOR I&C SUBSYSTEMS
- o DEMONSTRATED CAPABILITY TO SCALE SP-100 CONCEPT FOR A WIDE RANGE OF REQUIREMENTS AND CONCEPTS

TYPICAL OPTIMIZED PARAMETERS

CORE HEIGHT
PIN DIAMETER
PIN P/D RATIO
CLADDING THICKNESS
PLENUM LENGTH
REFLECTOR THICKNESS
FUEL PELLETS/CLADDING GAP

CONSTRAINTS

PEAK BURNUP
F.G. PRESSURE STRAIN
FCMI+FG PRESSURE STRAIN
MAX FUEL TEMP
REACTOR ΔP
REFLECTOR WORTH

- o SIZES AND PROVIDES MASS ESTIMATES IN SENSITIVITY OR OPTIMIZATION MODE

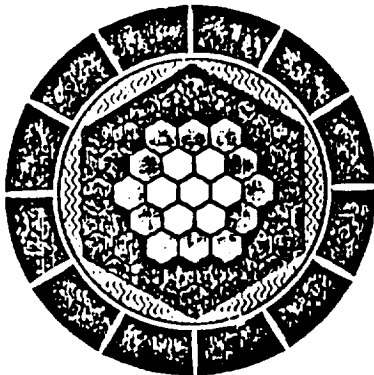


CORE CROSS SECTION SCHEMATIC

NASA

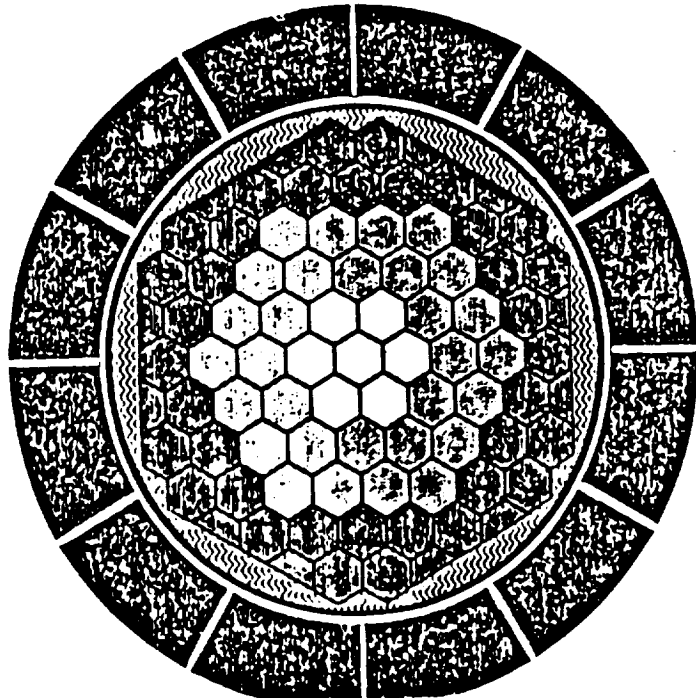
10MW

Number of full assemblies = 43
Number of partial assemblies = 12
Assembly pitch = 5.18 cm
Vessel outer radius = 21.6 cm
Reflector outer radius = 29.4 cm



50MW

Number of full assemblies = 73
Number of partial assemblies = 12
Assembly pitch = 8.09 cm
Vessel outer radius = 40.9 cm
Reflector outer radius = 56.4 cm



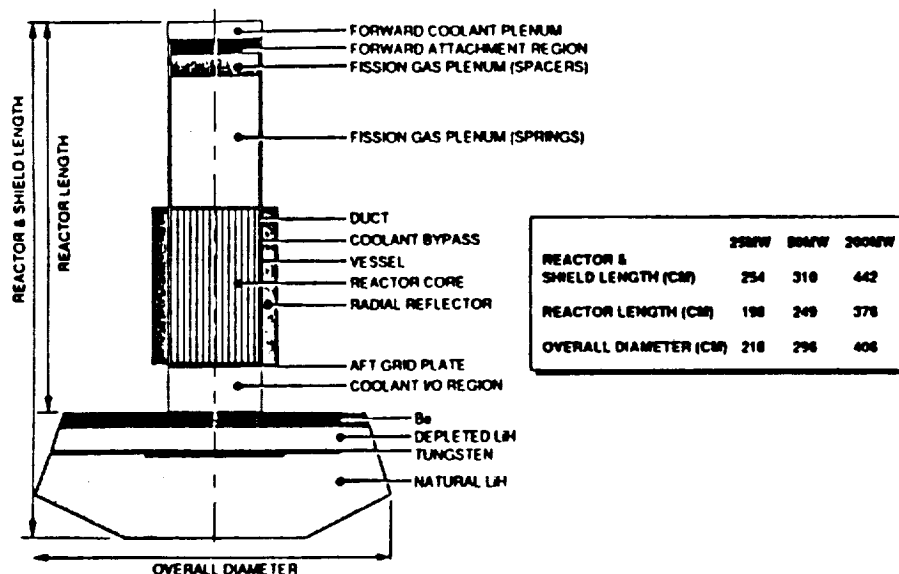
Core Zone 1	Bypass Coolant
Core Zone 2	Vessel
Core Zone 3	Radial Reflector

1/8 SCALE



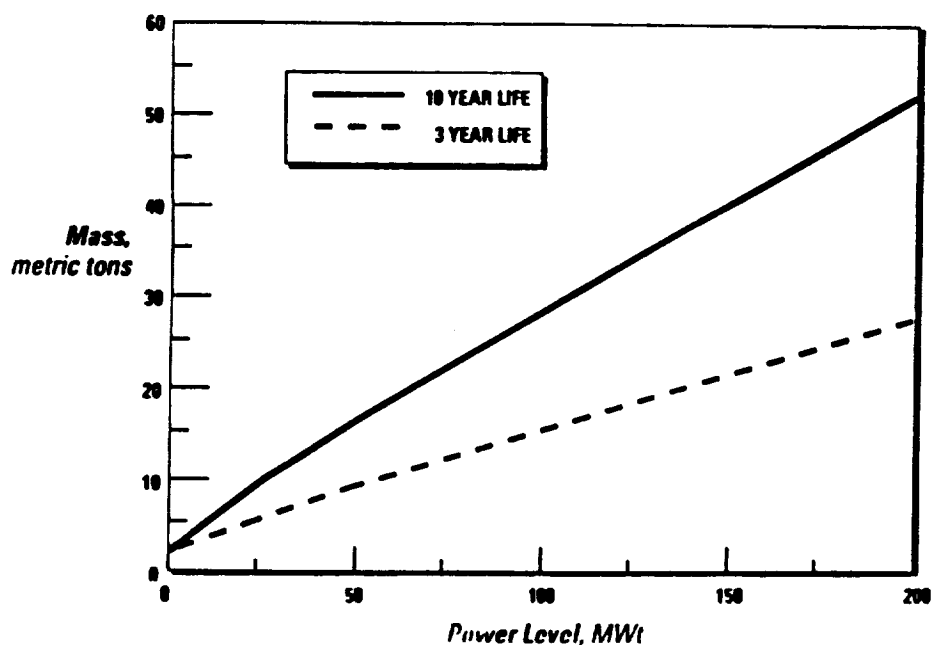
REACTOR R-Z SCHEMATIC

NASA



REACTOR SUBSYSTEM MASS vs LIFETIME

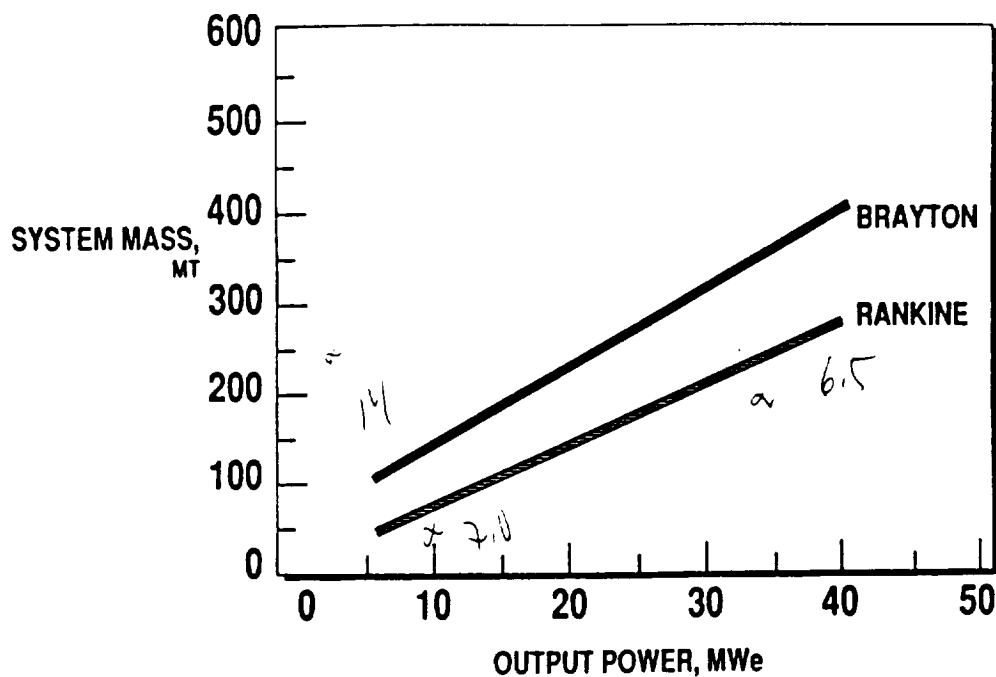
NASA





SYSTEM MASS vs OUTPUT POWER

LeRC



RJS-910 04 12



DEVELOPMENT NEEDS

NASA

- o NO TECHNOLOGY DEVELOPMENT ITEMS BEYOND GES
- o KEY FEATURE TESTS NEEDED
 - CRITICAL EXPERIMENT
 - SLIDING REFLECTOR
 - SCALED-UP CONTROL DRIVE
 - SCALED-UP PUMP
 - FLOW TEST
 - Li7H NUCLEAR HEATING TEST
 - EXTEND FUEL AND MATERIALS IRRADIATION DATA BASE



NASA

SDIO IEG STUDY

- SP-100 TECHNOLOGY FOR MMWe APPLICATIONS
- CHANGE CLAD —→ INCREASE TEMPERATURE
- PERFORMANCE EQUIVALENT TO PROPOSED LMC REACTOR SPECIFICALLY PROPOSED FOR ADVANCED CONVERSION

1600k



===== EXPLORATION TECHNOLOGY =====

SP-100 GROUND ENGINEERING SYSTEM STORY

ITP.RJS91-002.0



PHASE II PROGRAM OBJECTIVE

- DEVELOP AND DEMONSTRATE BY 1992 THAT THE TECHNOLOGY IS READY FOR FLIGHT APPLICATION OF 10 TO 1000 kWe SPACE REACTOR POWER SYSTEMS FOR FUTURE MILITARY AND CIVILIAN SPACE MISSIONS.



THE SP-100 GES PROGRAM

OBJECTIVE

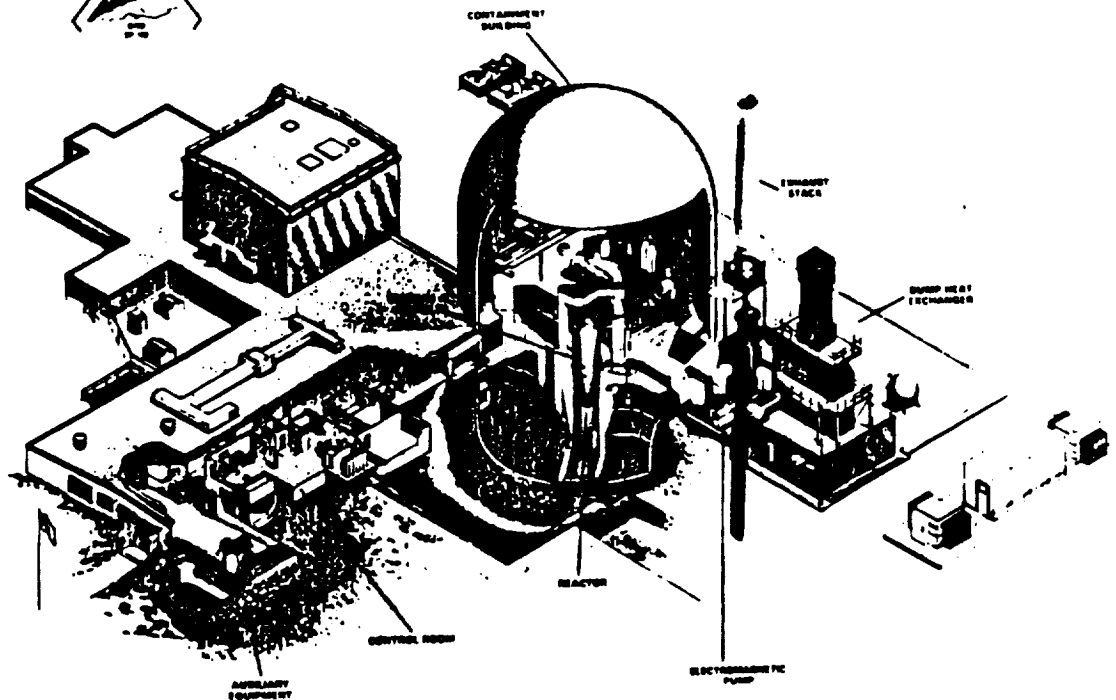
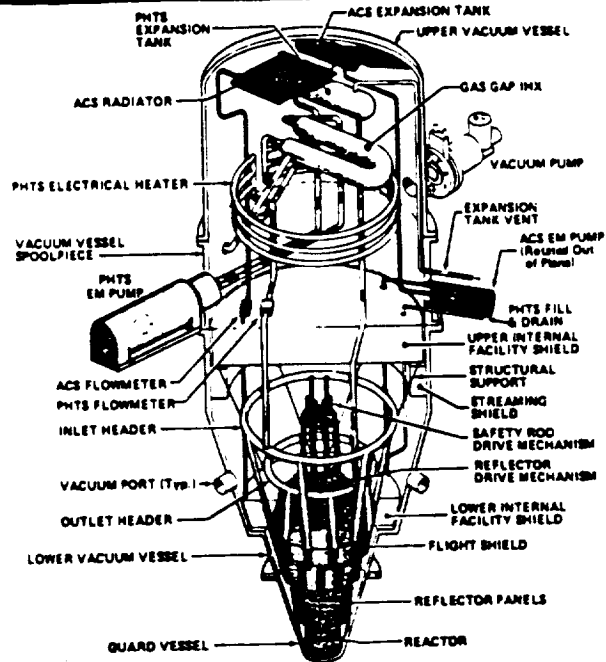
- CONDUCT THE ENGINEERING DEVELOPMENT AND GROUND SYSTEM TESTING OF A REACTOR SPACE POWER SYSTEM FOR POWER LEVELS OVER THE RANGE OF 10's TO 100's OF KILOWATTS ELECTRIC.

SCOPE

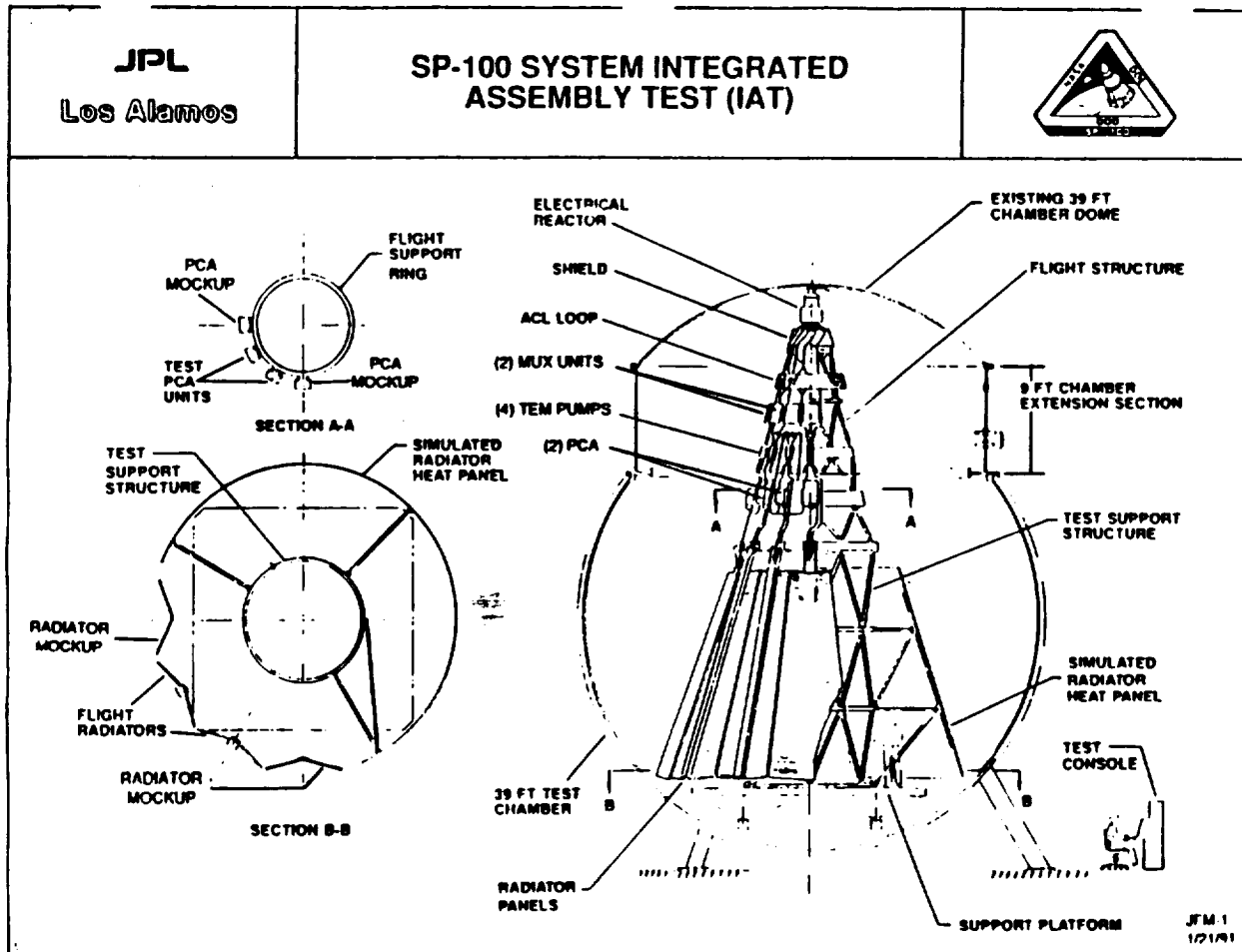
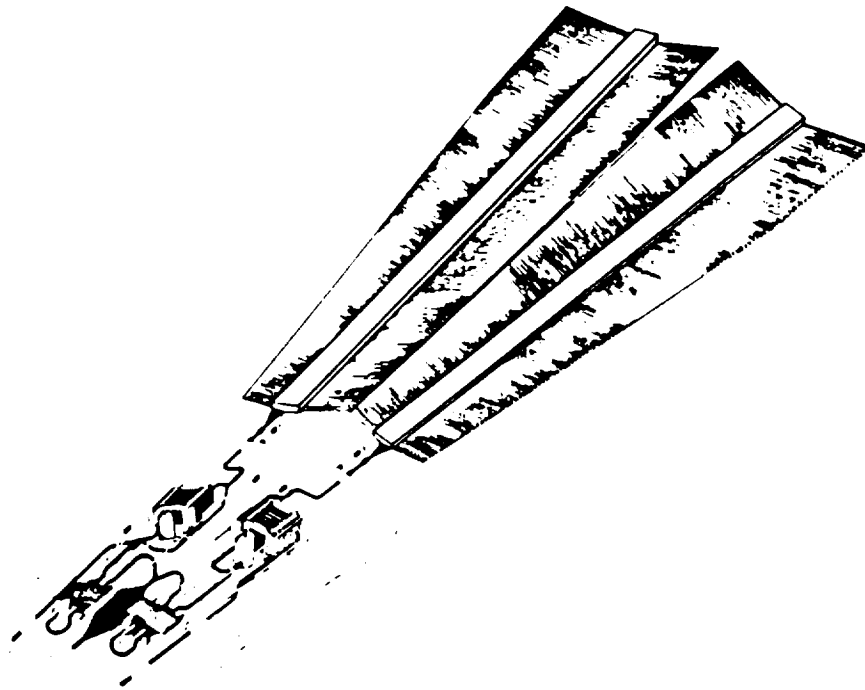
- SUBSYSTEM TECHNOLOGY OF THE COMPLETE POWER SYSTEM (DEMONSTRATE COMPONENT LIFETIME)
 - REACTOR AND SHIELD
 - THERMOELECTRIC POWER CONVERTER
 - HEAT TRANSPORT
 - HEAT REJECTION
 - INSTRUMENTATION AND CONTROL
 - POWER CONDITIONING, CONTROL, AND DISTRIBUTION
 - STRUCTURAL
- TWO MAJOR PERFORMANCE TESTS (DEMONSTRATION SYSTEM PERFORMANCE)
 - NUCLEAR ASSEMBLY TEST (NAT)
 - INTEGRATED ASSEMBLY TEST (IAT)
- SYSTEM EFFORTS
 - MANAGEMENT
 - SYSTEM DESIGN
 - RELIABILITY AND QUALITY ASSURANCE
 - SAFETY
 - SYSTEM STUDIES (SCALEABILITY, MAINTAINABILITY)



Test Assembly



ENERGY CONVERSION ASSEMBLY SEGMENT





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BASELINE COSTS (M\$)

FY	87	88	89	90	91	TOTAL
	122	153	148	115	77	641

- PROGRAM SCOPE/SCHEDULE ADJUSTMENTS HAVE BEEN REQUIRED AS RESULT OF CONTINUED BUDGET SHORTFALLS

GENERALLY - STRETCH NAT

- STRETCH/ELIMINATE SPACE SUBSYSTEMS EFFORTS
- INCREASE OVERALL BUDGET

FY	87	88	89	90	91
PLANNED	80	160	165	107	91
ACTUAL	64	94	77	78	50
RUNOUT	92	93	94		
	103	112	117		

RJS-910 04 16



LeRC

SP-100

PROGRAM REVIEW GROUP

1989 - 90

RJS-910 04 16



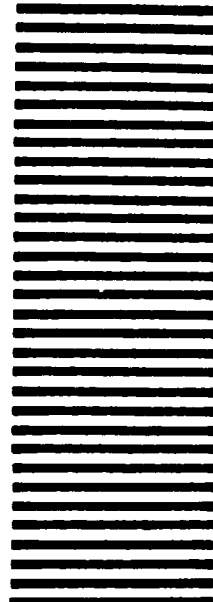
SP-100 PROGRAM REVIEW GROUP PRESENTATION



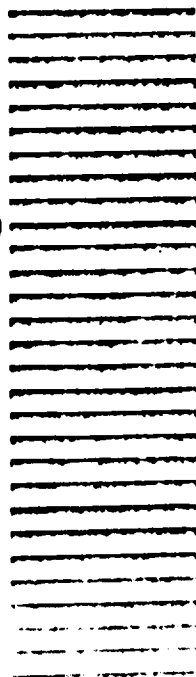
NASA



June 15, 1990



SP-100 PROGRAM REVIEW GROUP FINDINGS

- **There is a clear need for Space Reactor Power**
 - Enabling for NASA Space Exploration Initiative (earliest projected NASA application)
 - Enhancing for SDIO and USAF mission (USAF evaluating future role of space reactor power)
 - **Top level SP-100 requirements are still appropriate**
 - Power range (10's to 100's kWe)
 - Lifetime (7 years full power)
 - **Decision to select thermoelectric conversion still appropriate**
- 

SP-100 PROGRAM REVIEW GROUP FINDINGS

(continued)

- **Significant progress has been made by the SP-100 Program**
 - Hardware being fabricated
 - Major advancements in thermoelectrics and fuel rod construction
 - Technical areas of concern in reactor and converter being addressed
 - Funding shortfalls are the principal threat to balanced technical progress

SP-100 PROGRAM REVIEW GROUP FINDINGS

(continued)

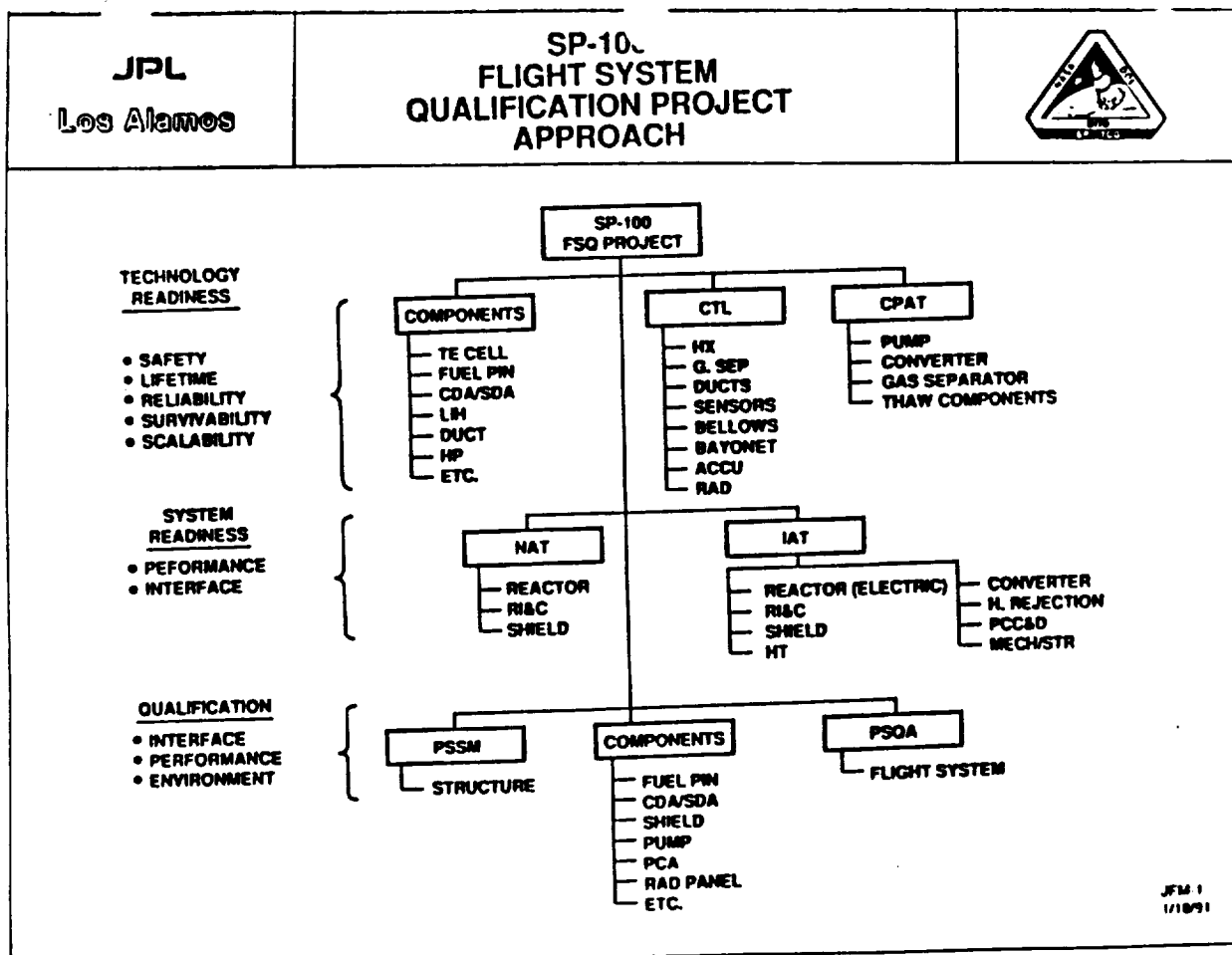
- **There is a major deficiency in the current program**
 - Development effort is limited to reactor and converter
 - Key overall system development not being addressed
 - Key technical areas in non-nuclear space subsystems not being addressed (e.g., heat rejection)



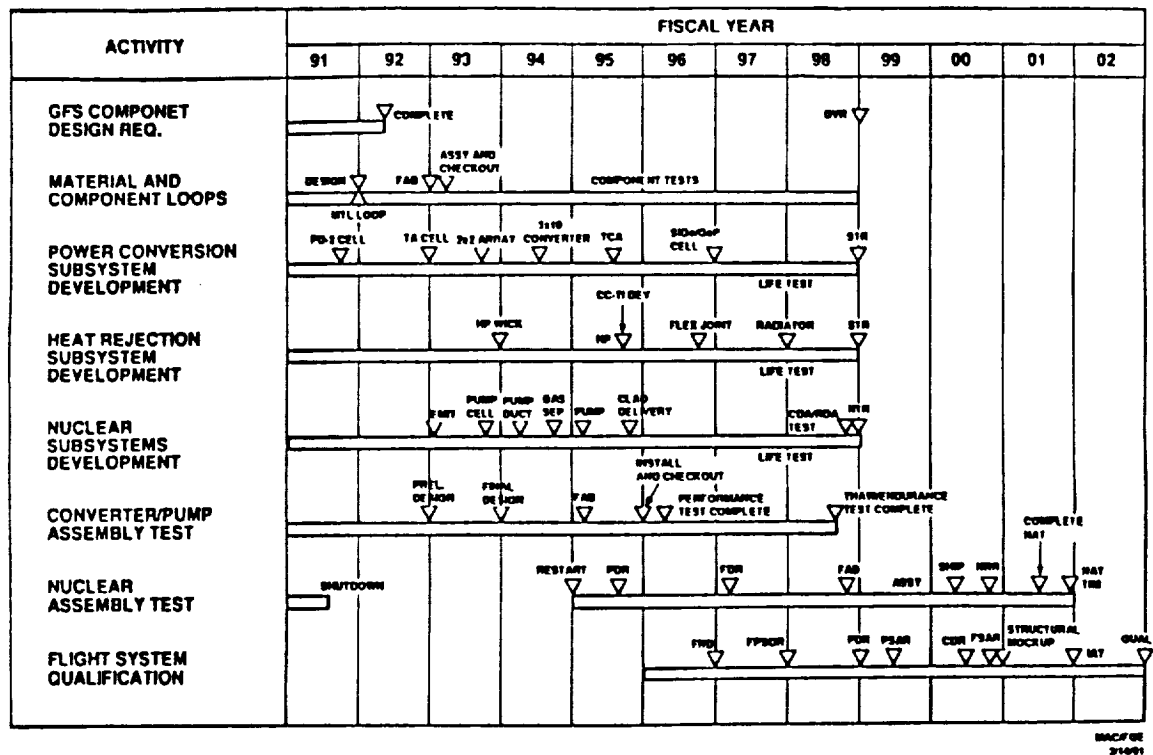
1991 REDIRECTED FLIGHT SYSTEM QUALIFICATION

- RE-ORIENT TO COMPONENT DEVELOPMENT FOCUS
- DELAY NAT
- DEMONSTRATE EARLY COMPLETION OF NUCLEAR AND SPACE TECHNOLOGY READINESS - 98
- EARLY CONVERTER/PUMP ASSEMBLY TEST - 96
- REDESIGN OF NUCLEAR ASSEMBLY UPDATE
- LEAST SENSITIVE TO FUNDING DISRUPTIONS

RJS91-003.7



SP-100 FLIGHT SYSTEM QUALIFICATION PROGRAM SUMMARY SCHEDULE



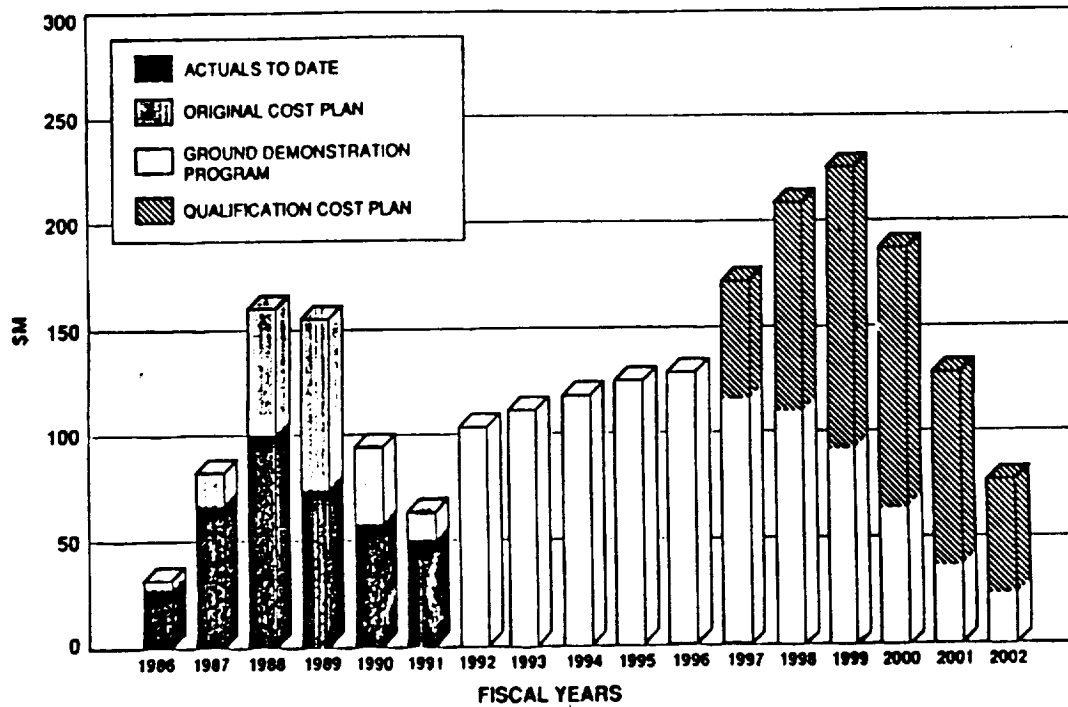
SP-100 GES PROGRAM STATUS & OPTIONS

LeRC

- **GES PROGRAM**
 - THRU FY90 \$320M HAS BEEN SPENT -
 - ~ \$240M FOR NUCLEAR SUBSYSTEM
 - ~ \$ 80M FOR SPACE (NON-NUCLEAR) SUBSYSTEM
- **CURRENT FSQ PROGRAM**
 - WITH EXPECTED (PLANNED) ANNUAL FUNDING RATE A TRL 6
 - CAN BE ACHIEVED IN 2001 WITH TOTAL FUNDING OF \$1284M THRU FY2001
 - \$1064M FOR NUCLEAR SUBSYSTEM
 - \$ 220M FOR SPACE (NON-NUCLEAR) SUBSYSTEM
- **OPTIONAL ACCELERATED PROGRAM**
 - CAN ACHIEVE A TRL 6 BY 1997 FOR \$1145M

	FY	92	93	94	95	96	97	TOTAL
REQ'D FUNDING RATE		125	170	225	235	220	170	1145
PLANNED FUNDING RATE		103	110	115	123	130	110	691
ADD'L FUNDING NEEDED		22	60	110	112	90	60	454

FSQ PROGRAM COST



Spent to date 240 80 Spent

ATM-4
2/19/91



===== EXPLORATION TECHNOLOGY =====

TECHNICAL PROGRESS



GFS Design Options New Features

HEAT TRANSPORT

- Smaller pumps
- Improved thaw

SHIELD

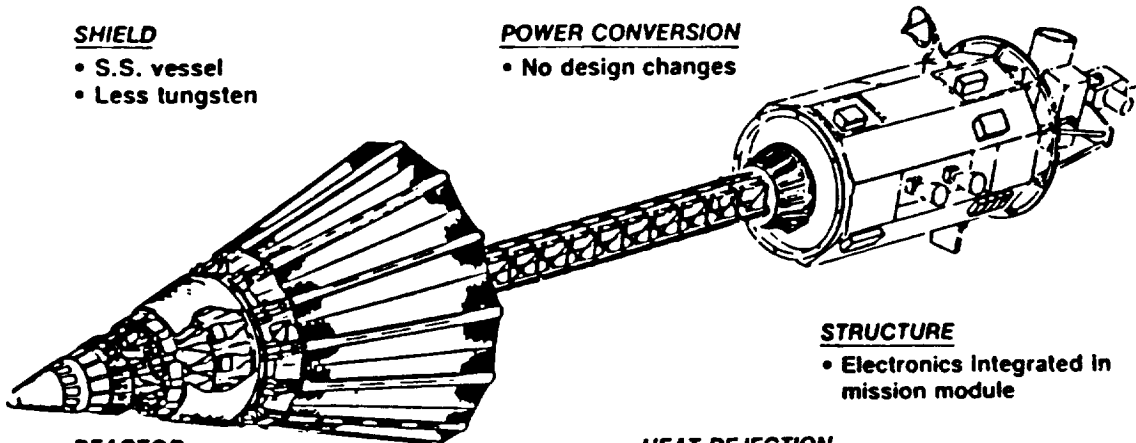
- S.S. vessel
- Less tungsten

POWER CONVERSION

- No design changes

PCC&D

- Advanced packaging



STRUCTURE

- Electronics integrated in mission module

REACTOR

- 3 safety rods
- Sliding reflector control
- Optimized fuel pin
- Axial reflector
- Optimized hex core structure


RI&C

- Neutron monitor

HEAT REJECTION

- C-C armored heat pipes
- Double duct
- Aft folding radiator

NFS23

JPL Los Alamos	FIVE CANDIDATE THAW SYSTEMS	
	<ul style="list-style-type: none">o AUXILIARY COOLANT LOOP/NAK TRACE LINE/SEQUENTIAL THAW (ACT)o AUXILIARY COOLANT LOOP/BLEED TUBEo BLEED TUBE THAW CONCEPTo HEAT PIPE THAW CONCEPTo SEQUENCED ELECTRICAL HEATER CONCEPT	



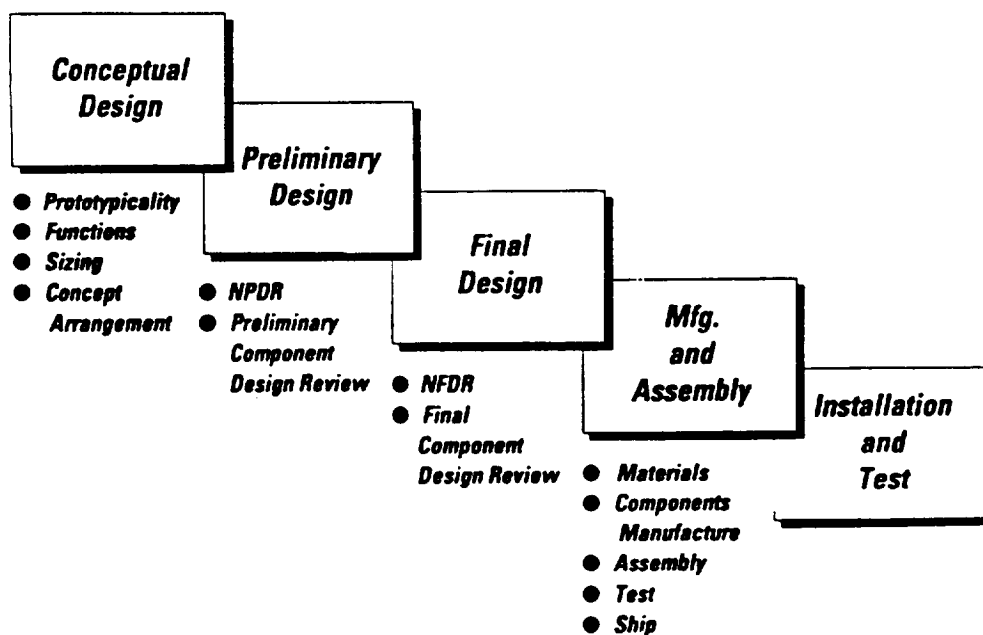
SP-100 GES PROGRESS

- GENERIC REFERENCE FLIGHT SYSTEM DESIGN
- SUBSYSTEM AND COMPONENT SPECIFICATIONS
- MATERIALS, PROCESS AND FABRICATION SPECIFICATIONS
- VALIDATION PLAN
- EIS, FONSI , ETC., FOR FACILITY

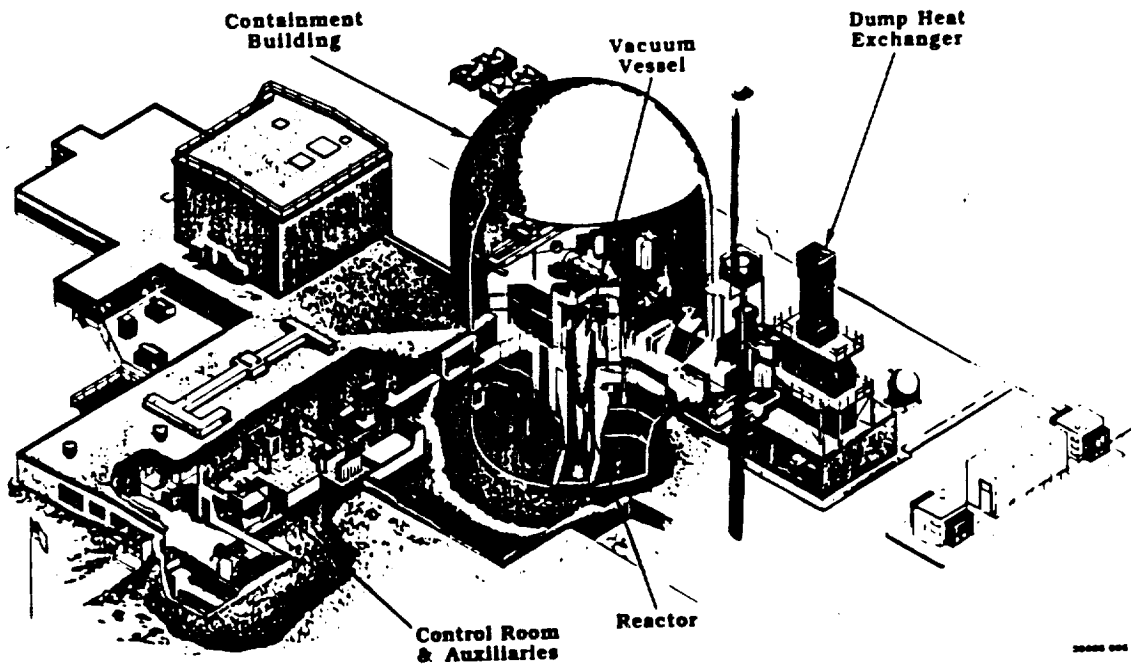
RJS91-003.14



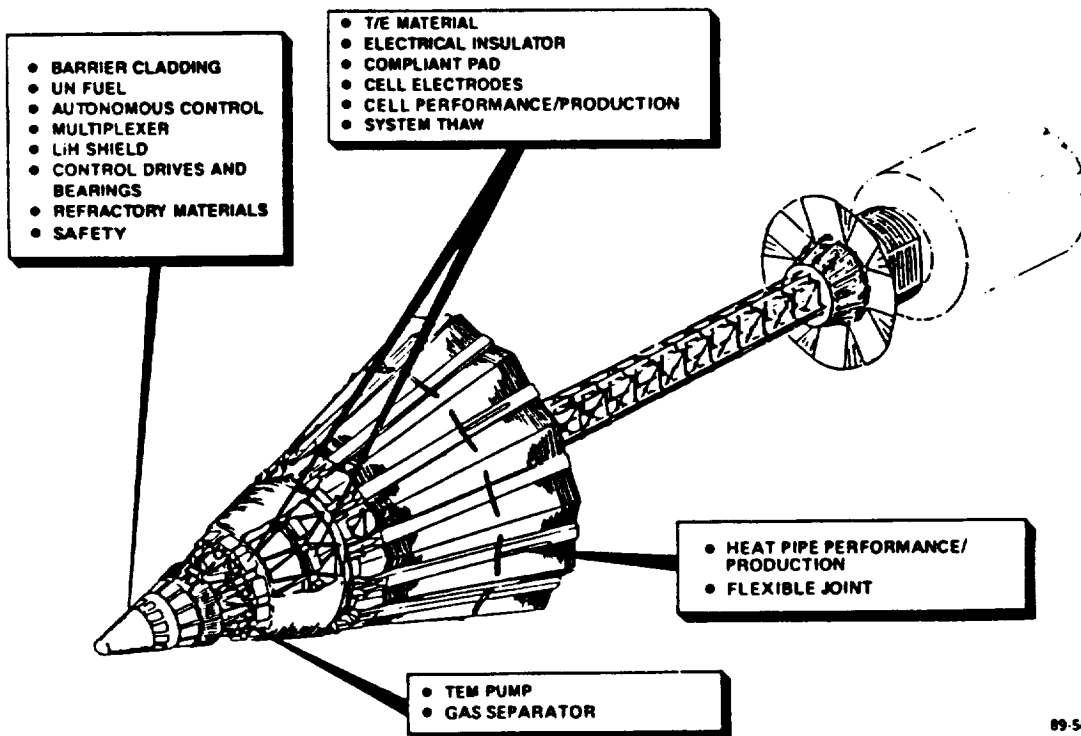
Nuclear Assembly Test Progress



NSS 084 90-520-35

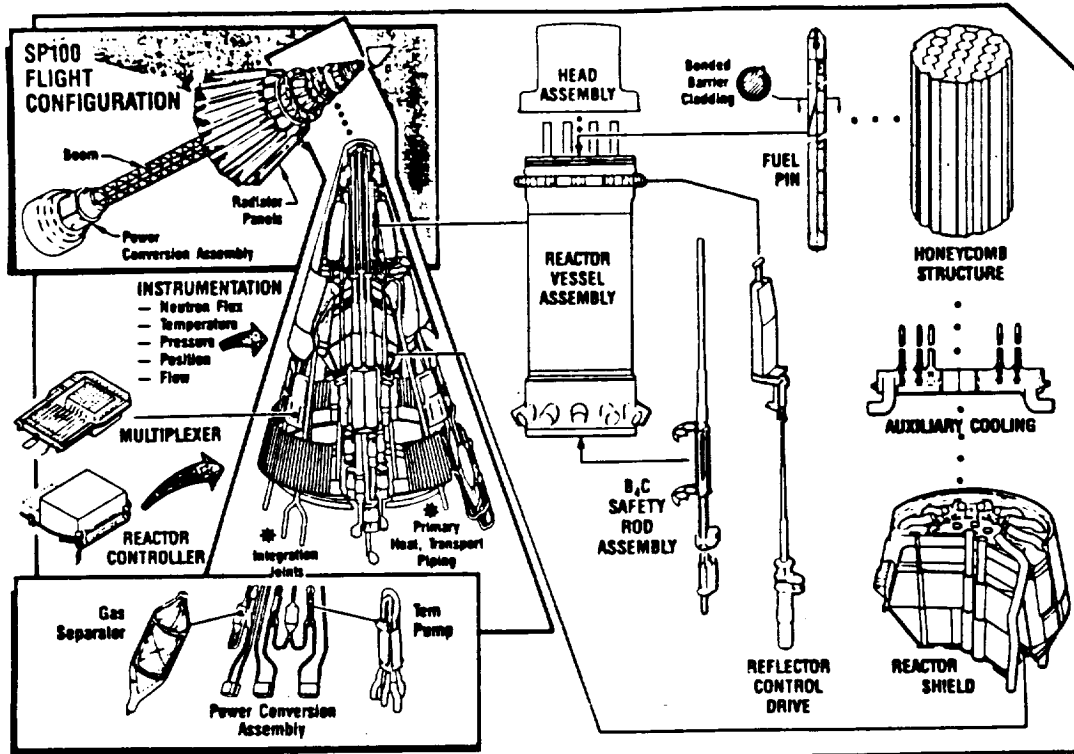


SP-100 Key Technologies





SP-100 GENERIC FLIGHT SYSTEM NUCLEAR SUBSYSTEM KEY TECHNOLOGIES



88-111-02



SP-100 Uranium Nitride Fuel

- **Process Developed at Los Alamos National Laboratory**
- **Meets Exacting GE Specifications**
 - Chemistry
 - Dimensions
 - Density
 - Microstructure
 - Quality Assurance
- **Pellet Production for Nuclear Assembly Test Nearing Completion**

NSS 055 90-520-24



*UN Fuel Manufacturing
at Los Alamos*



SP-100 Uranium Nitride Fuel



MSS 052 90-520-22



- Total NAT fuel pellets required
49,000 - 97 % enriched
~ 6600 - 89 or 93 % enriched (depends on GFS updated design)
- Total NAT fuel pellets currently fabricated
44,400 - 97 %
zero - 89 or 93 % (93 % enrichment feedstock available)
- Total fuel pellets requiring resintering
44,400 - 97 %
- Fuel pellets currently resintered
9700 - 97 %

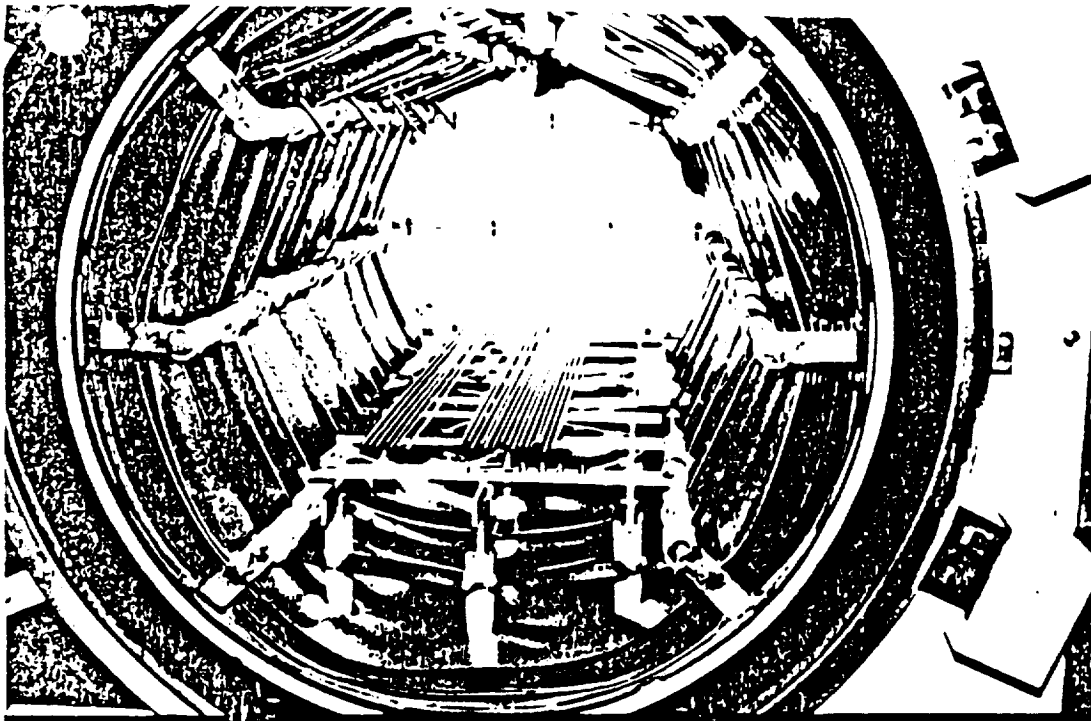
3/18/91



SP-100 Materials Technology

- *Demonstrated Fabricability of Re Lined Nb-1Zr (Barrier) Fuel Cladding*
- *Demonstrated High Creep Strength of Barrier Cladding*
- *Demonstrated Effectiveness of Chemistry Control and/or Heat Treatment in Preventing Li Attack of Nb-1Zr Welds*
- *Demonstrated High Temperature Strength of Controlled Chemistry Nb-1Zr*
- *Demonstrated Dynamic Friction Properties of ZrC and HfC Hardfacings Under High Temperature (1600°K) High Vacuum (10⁻⁸ Torr) Conditions*

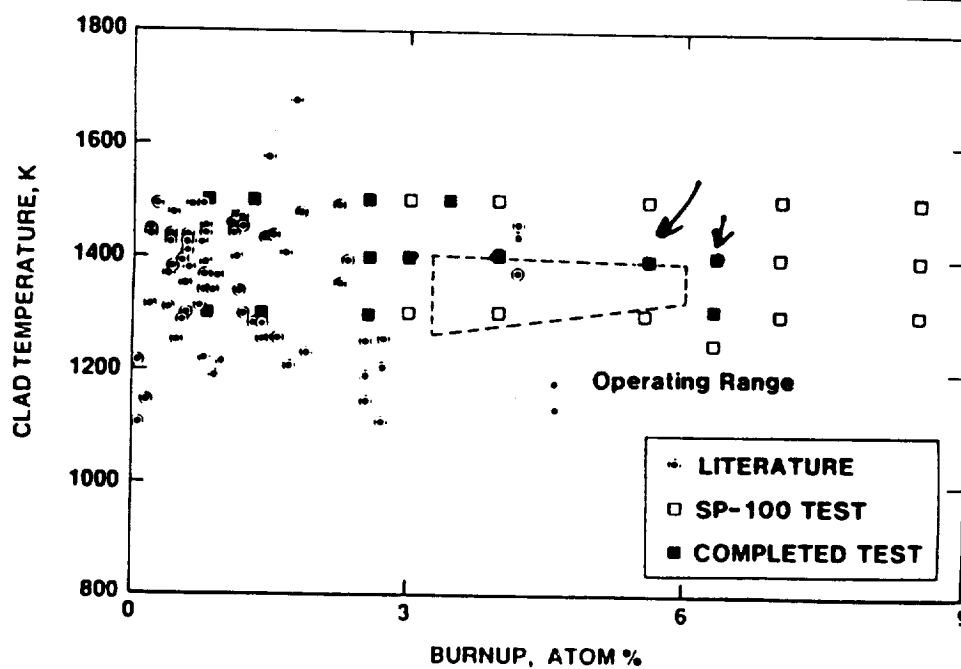
Mum to PWC-11



**22 TUBES OF QUALIFICATION BATCH 1 IN THE
VACUUM HEAT TREAT FURNACE AFTER BEING
DRAWN TO FINAL SIZE**



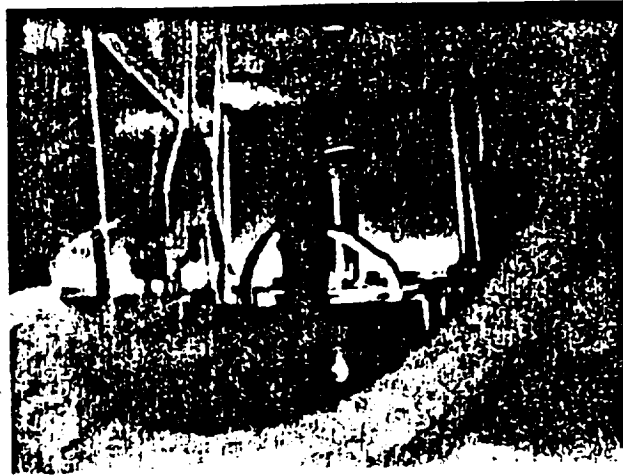
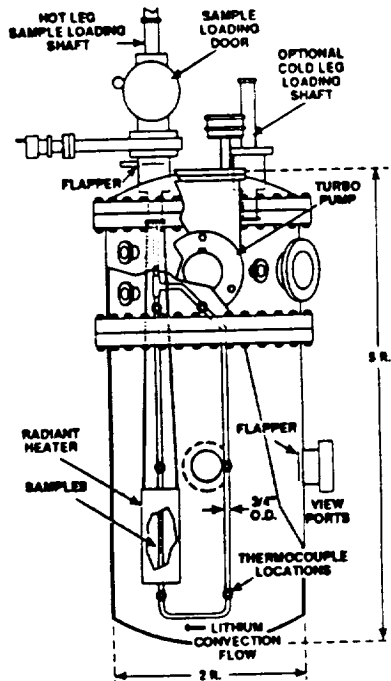
Fuel Pin Supporting Data



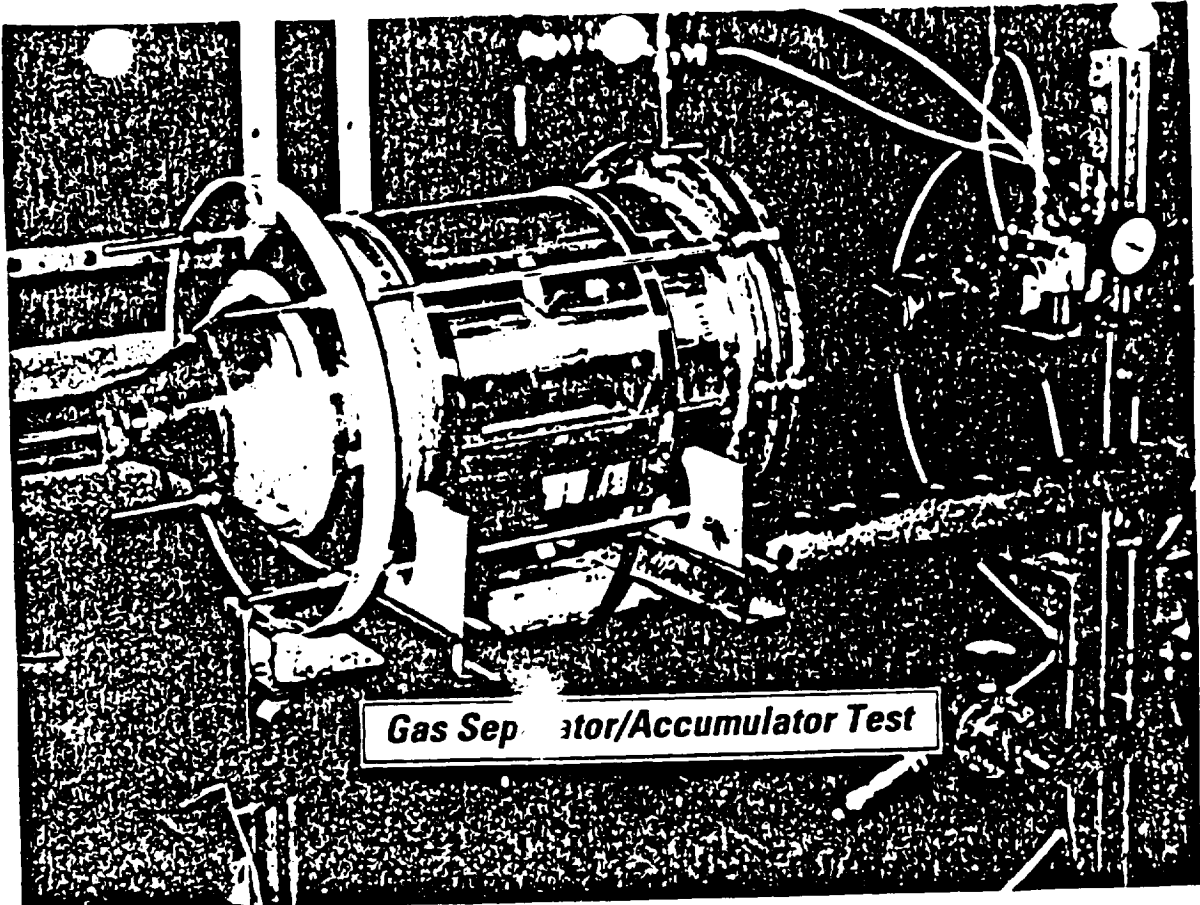
90 284 01



Materials Test Loop



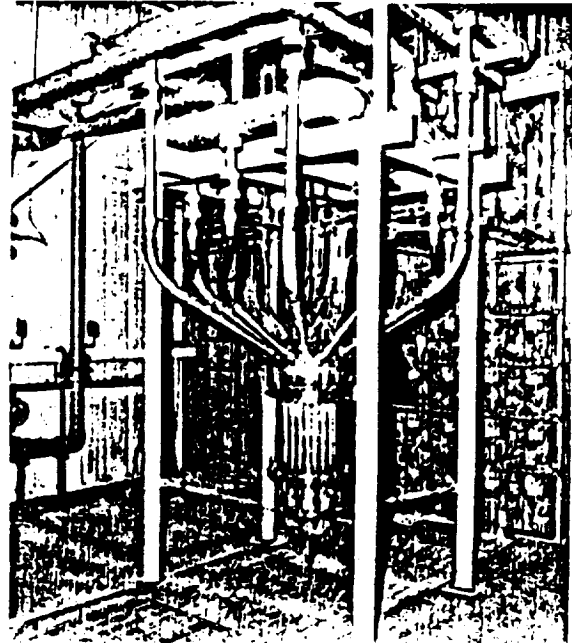
NSS 084 80-520-33





SP-100 Full Scale Hydraulic Flow Test

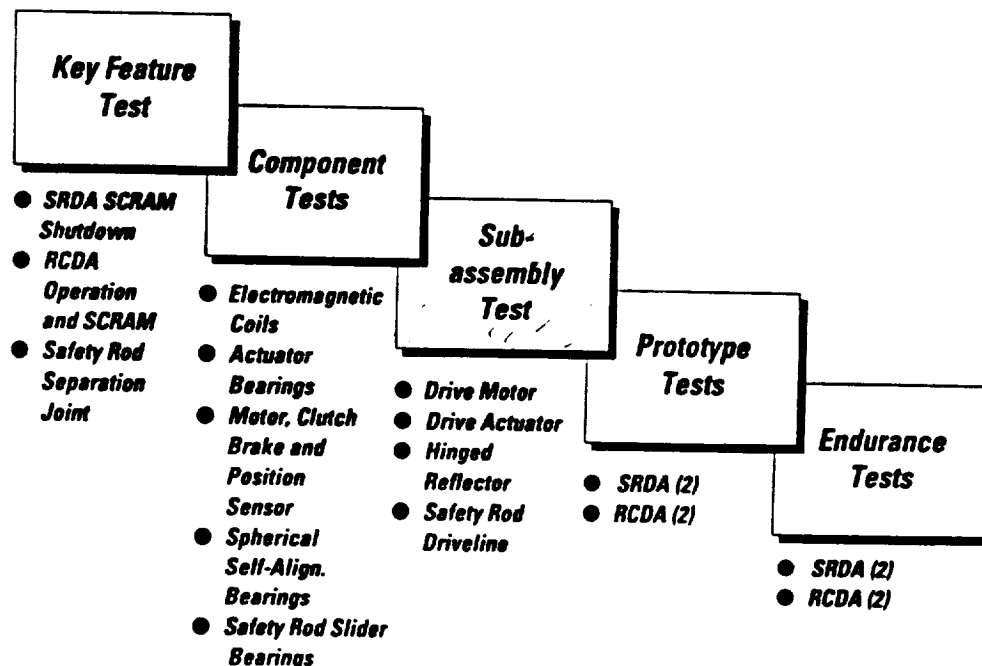
- **Measured Overall Pressure Drop**
- **Measured Coolant Flow Distribution Within Reactor Core**
- **Verified Orifice Sizing Predictions**
- **Investigated Reactor Hydraulic Characteristics:**
 - Entrance to Annulus Losses
 - Annulus to Core Entrance Losses
 - Exit Plenum to Reactor Outlet Losses
 - Effects of Inlet Pipe Blockage on Coolant Distribution
- **Tests Complete**



NSS 063 90-520-23



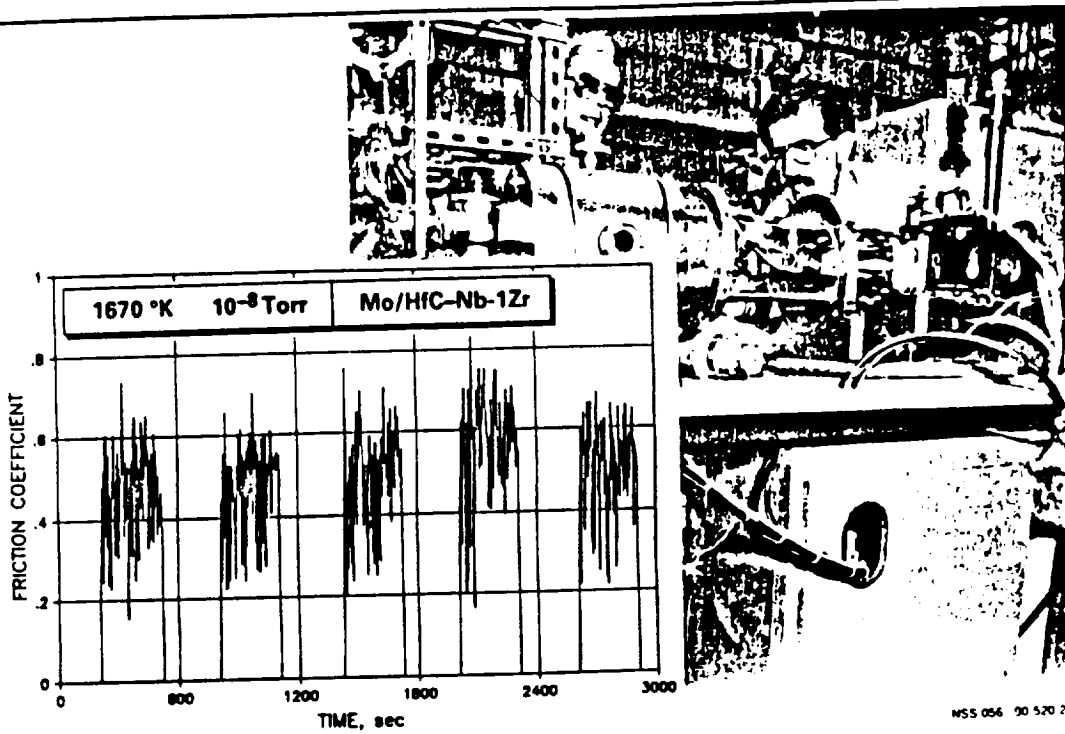
Control Drive Development



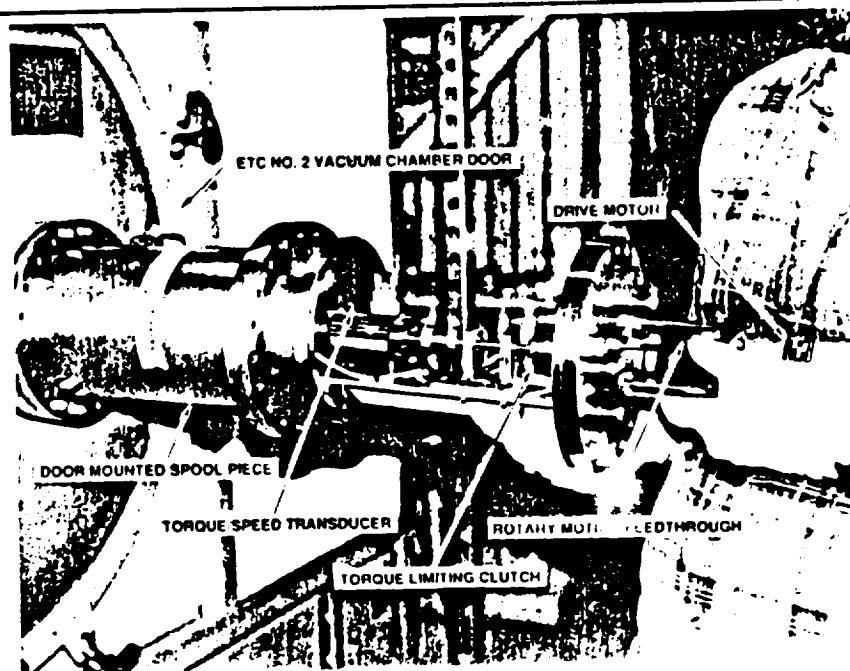
NSS 070 90-520-39



High Temperature Tribology



Control Drive Self-Aligning Bearing Test

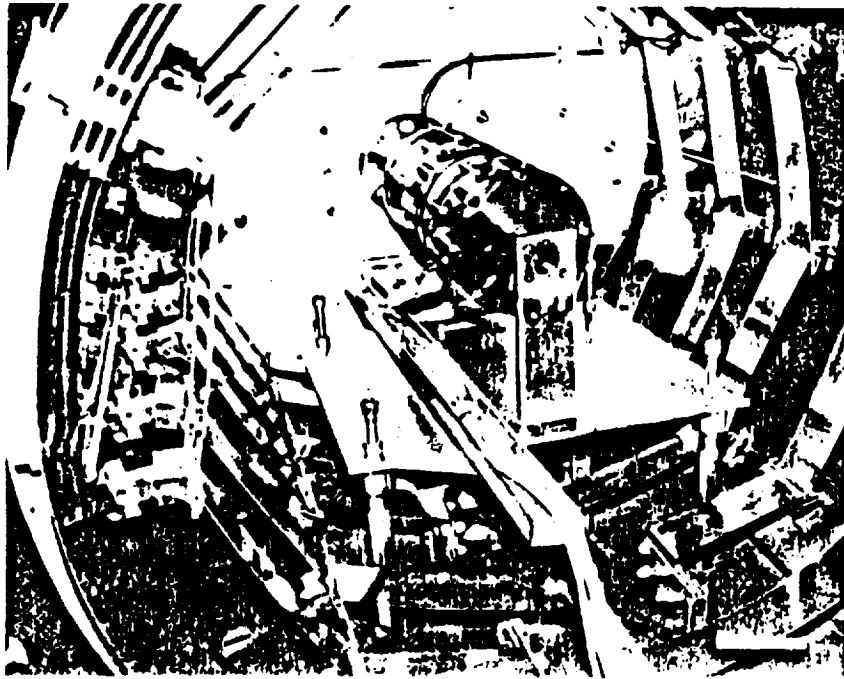


NSS 057 90 520 26

ORIGINAL FACTOR
OF POOR QUALITY



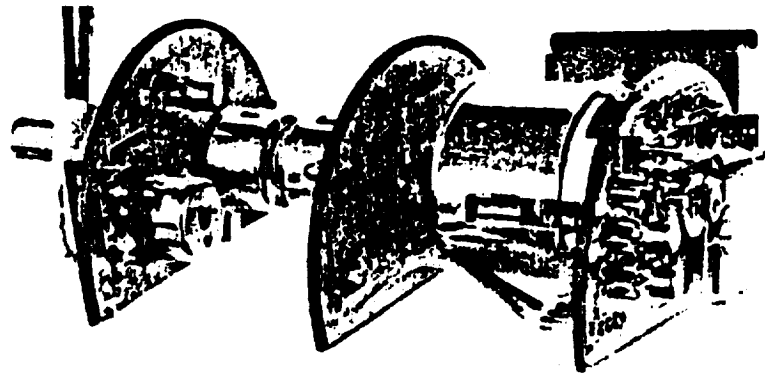
Control Drive Clutch/Resolver Test



NSS 058 90-520-27



Multiplexer Development



Gamma:

- No JFET Damage
- 50 °C
- Dose Acceleration 15:1

Neutron:

- 40% JFET Damage
- 50 °C
- Dose Acceleration 120:1

Acceptable Performance Expected at Lower Dose Rates & Higher Temperatures

NSS 063 90-520-32



HEAT TRANSPORT SUBSYSTEM

- TE-EM PUMP MASS AND EFFICIENCY
- TEM PUMP TE CELL

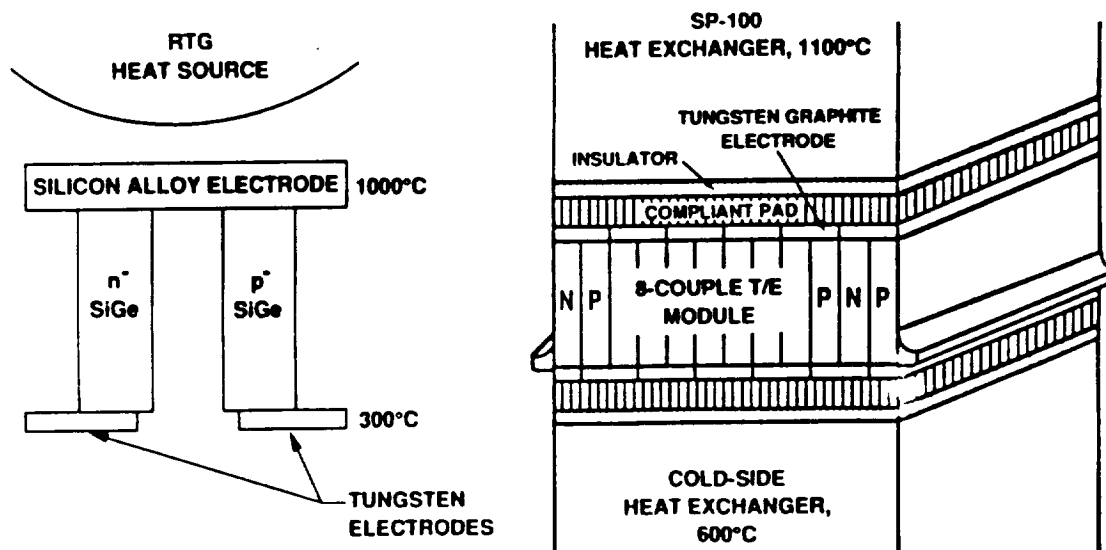
POWER CONVERSION SUBSYSTEM

- HIGH VOLTAGE INSULATOR
- COMPLIANT PAD
- ELECTRODES
- TE CELL ASSEMBLY
- IMPROVED SiGe

HEAT REJECTION SUBSYSTEM

- HEAT PIPE
- RADIATOR DUCT THAW

JM 33

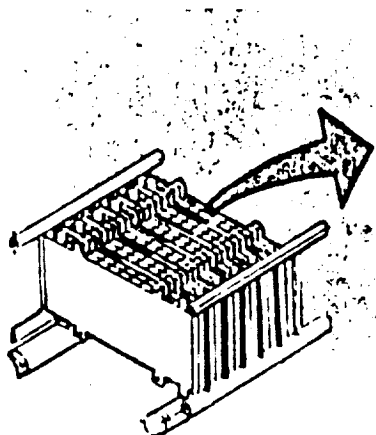


CE 3
2/15/91

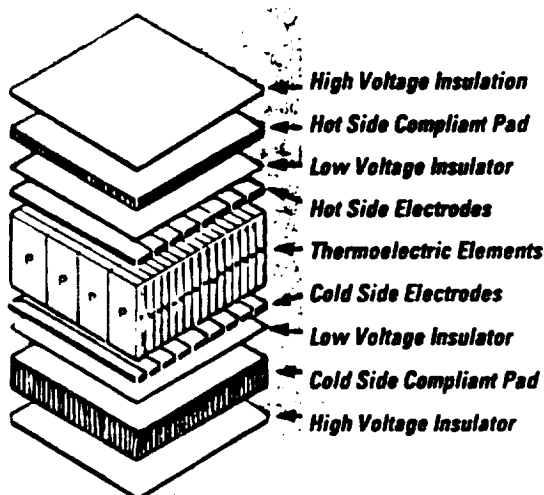


Power Converter Cell Configuration

**Power Converter
Assembly**



**Cell
Assembly**



SPAC 02580-520-03



High Voltage Insulator

- **Accelerated Life Tests Have Demonstrated Substantial Performance and Life Margins**
 - High Temperatures (Up to 1670° K)
 - High Voltage Gradient (4 kV/cm)
 - Long Times (Up to One Year)
- **Compatibility With Li Cooled Systems Proven by Analysis and Test**
- **Mechanistic Degradation Models Developed and Validated**



Essential Technology Demonstrated

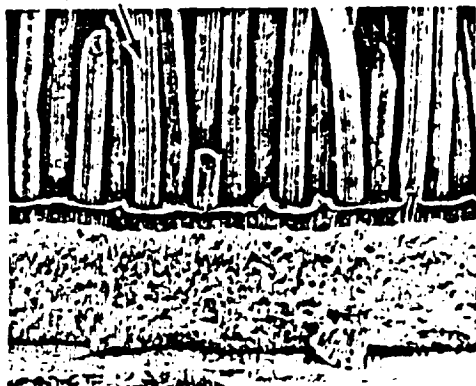
SPAC 032 99-520-10



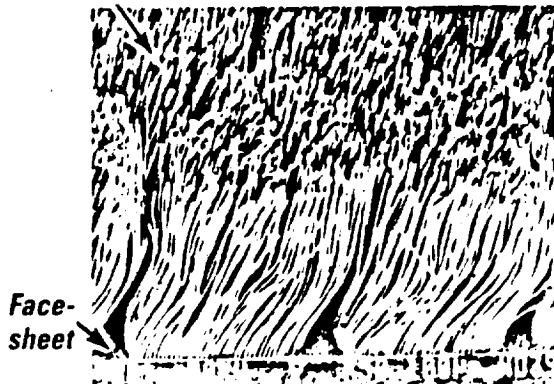
Compliant Pad



Filaments



Filament Bundles



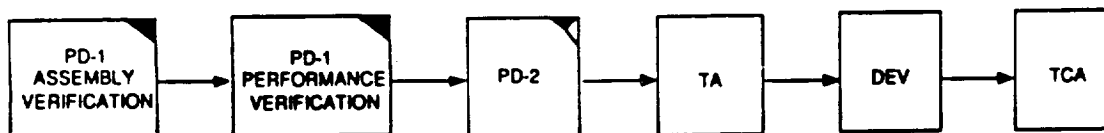
SMAC 027 00 5-13 05

- ① Fabricability Demonstrated
 - Facesheet Materials/Thickness
 - Filament Diameters/Density
 - Pad Thickness
- ② Bond Strength Demonstrated
- ③ Compliance Demonstrated
- ④ Design Optimization Proceeding



Space Subsystems Cell Assembly

Cell Development Road Map



March 1989

Verified Fabrication and Assembly Processes

Demonstrated Structural Integrity

Show and Tell

September 1989

Verified Predictability of Performance

Demonstrated Structural Integrity

Lessons Learned for PD-2

Hot Side Temperature Limited by Braze

March 1991

Test at Full Prototypic Hot Side Temperature

Closer to Prototypic Design Features

Verify Performance

October 1992

Prototypic Configuration

Verify Performance

Demonstration of Technology Features of GFS Design

Prototypic Configuration

First Array Tests

Cell Life Tests

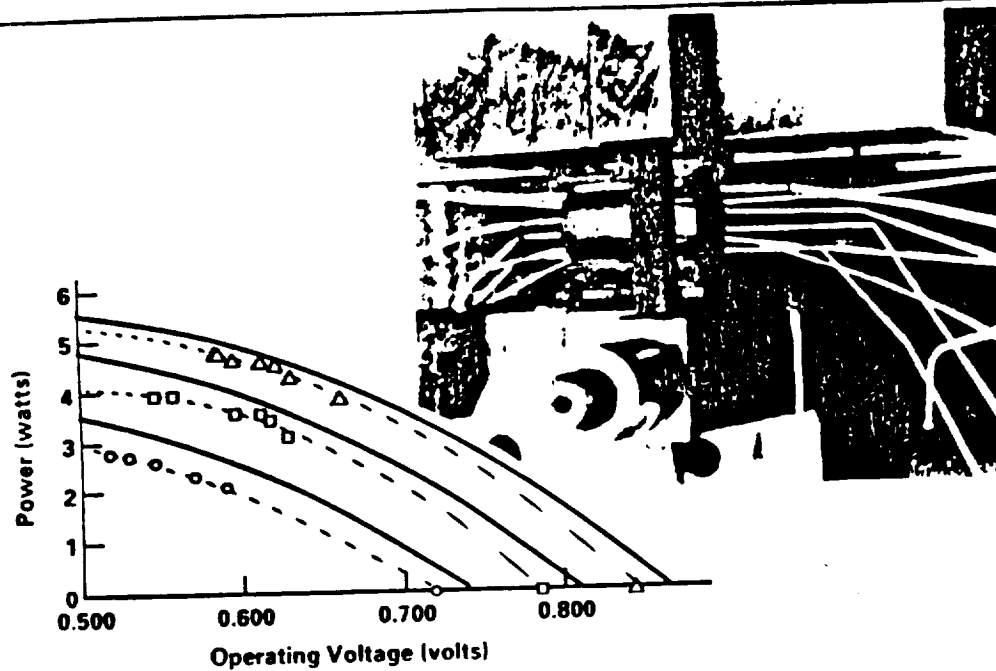
Prototypic Configuration and Operating Conditions

Converter/Pump Test

Array Life Tests



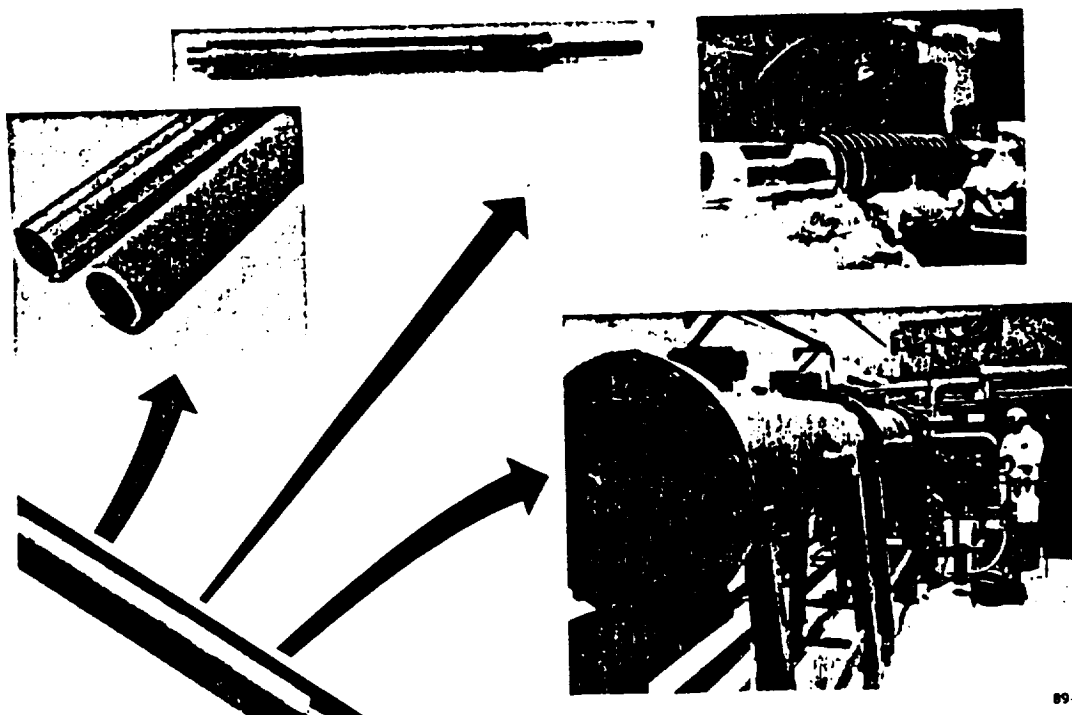
First Generation Cell In-Gradient Test



SPAC 626 '90 570 06



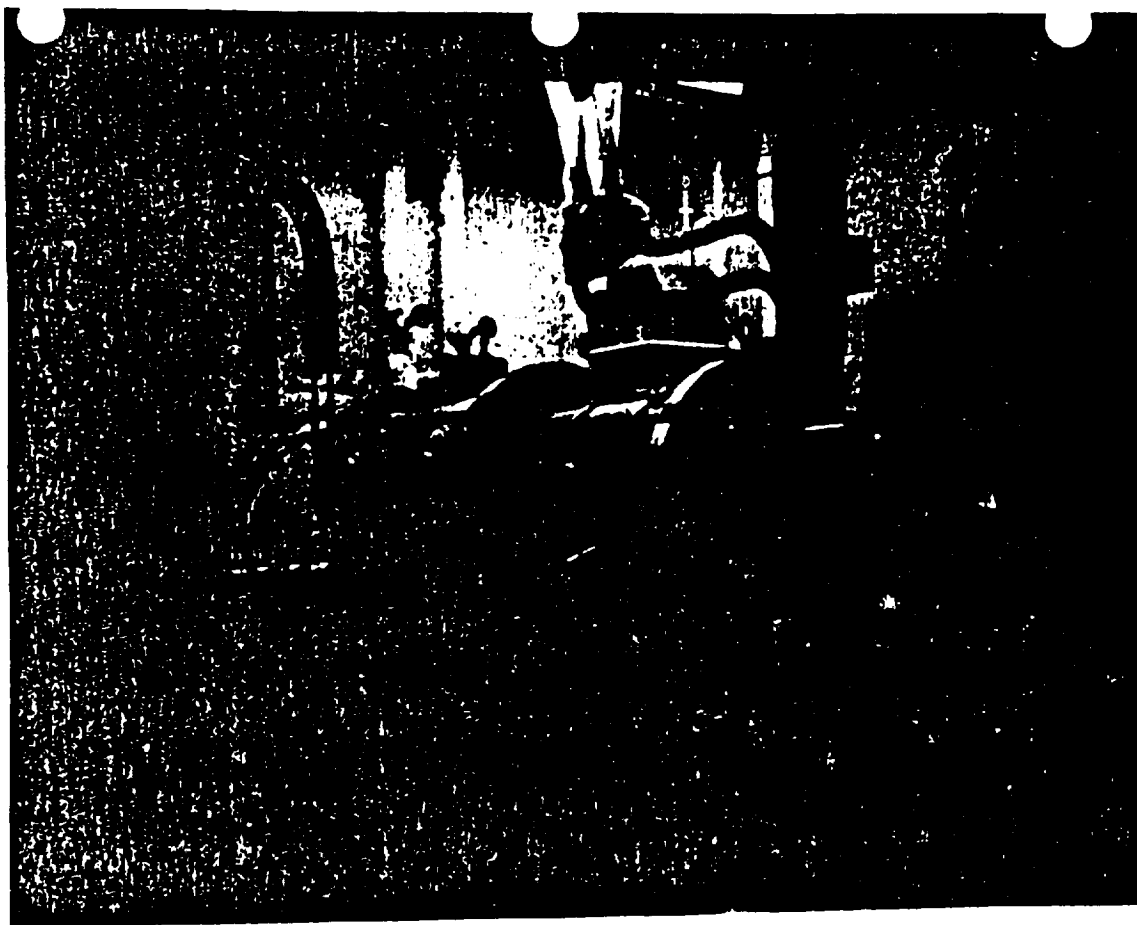
Potassium Heat Pipe Development





O POTASSIUM HEAT PIPE ACCOMPLISHMENTS

- DEVELOPMENT OF ETCHED TITANIUM FOIL WICKS (PREFERRED TECHNOLOGY)
- DEVELOPMENT OF SINTERED TITANIUM WICKS
- DEMONSTRATED PERFORMANCE OF $Nb_{12}Zr$ HEAT PIPES WITH FOIL WICKS
- PRELIMINARY DEMONSTRATION OF RADIATOR THAW CONCEPT,
DUCT WITH BLEED HOLES



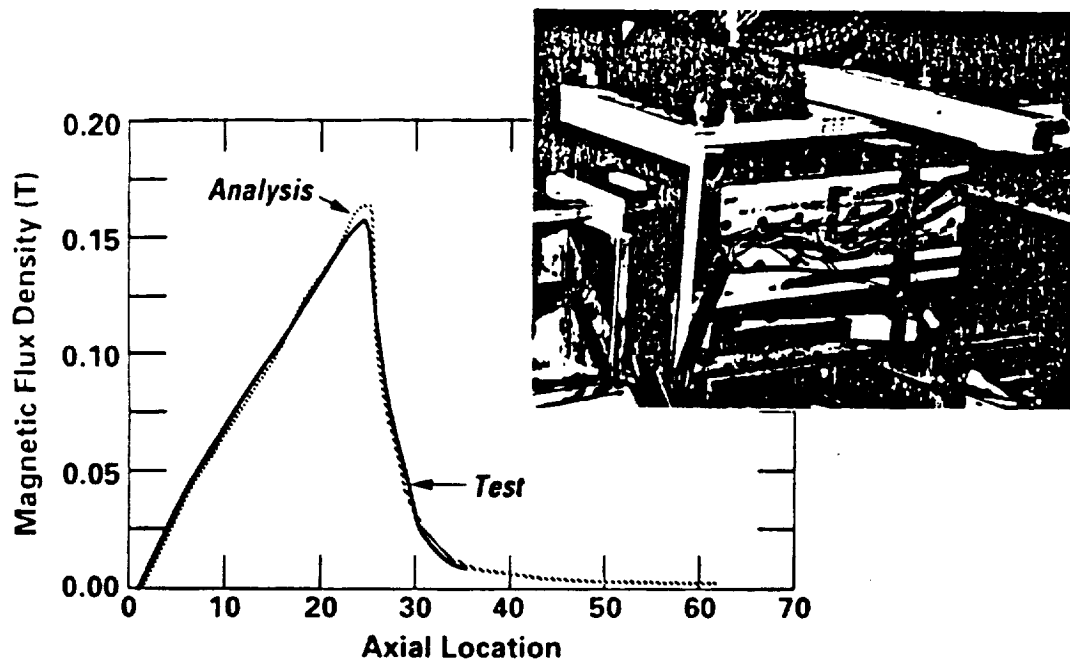
POLAROID
E019 7976 C

PT7-41

C-3



TEM Pump Magnetic Bench Test



NSS 098 90-520-26



EXPLORATION TECHNOLOGY

SPACE NUCLEAR POWER - SP-100 SUMMARY

- **IMPACT:**
 - PROVIDES ENABLING TECHNOLOGY FOR LUNAR/MARS BASES
 - POWER SOURCE FOR 1 - 100 kW_e NEP FOR EARLY 21st CENTURY SCIENCE MISSIONS NOW BEING CONSIDERED
 - REACTOR TECHNOLOGY FOR MMW_e NEP SYSTEMS FOR MARS CARGO AND PILOTED SPACE EXPLORATION MISSIONS
- **USER COORDINATION:**
 - SEI TECHNOLOGY REQUIREMENTS ARE BEING DEVELOPED COOPERATIVELY WITH CODE RZ (NUCLEAR POWER IDENTIFIED AS A HIGH PRIORITY AND ENABLING BY CODE RZ)
 - PLANETARY SCIENCE REQUIREMENTS ARE BEING DEVELOPED COOPERATIVELY WITH OSSA AND WITH JPL (NUCLEAR POWER RATED AS A HIGH PRIORITY BY OSSA IS ENABLING FOR MANY MISSIONS)
- **MAJOR TECHNICAL PROGRAMMATIC ISSUES:**
 - GENERIC TECHNOLOGY DEVELOPMENT - MEETS ALL POTENTIAL USER NEEDS
 - ABSENCE OF SPECIFIC APPROVED PROGRAM USING NUCLEAR POWER CONFUSES FIRM TECHNOLOGY READINESS REQUIREMENT DATE

ITP-RJS81-002.11



CONCLUDING REMARKS

- SP-100 IS THE NATIONAL NUCLEAR SPACE POWER PROGRAM
 - NATIONAL LEVERAGE
- PROVIDES A WIDE RANGE OF OPTIONS
 - FEW kWe's — MMWe
- MAJOR IMPACT ON EXPLORATION MISSION
- EXCELLENT TECHNICAL PROGRESS
 - FUNDING DIFFICULTIES
- FULL-UP PROGRAM
 - DEMONSTRATES USER SUPPORT/LEVERAGE
 - TECHNICAL SUCCESS

ITP-RJS91-002.10



EXPLORATION TECHNOLOGY

INTEGRATED TECHNOLOGY PLAN
FOR THE CIVIL SPACE PROGRAM

HIGH CAPACITY POWER

BY

R. J. SOVIE

Deputy Chief, Power Technology Division
NASA Lewis Research Center

ITP EXTERNAL REVIEW

JUNE 27, 1991

ITP91-002.1



EXPLORATION TECHNOLOGY

HIGH CAPACITY POWER

WHAT WE WILL DISCUSS

- OBJECTIVES/BENEFITS
- MAJOR MILESTONES/SCHEDULE/BUDGET
 - BASELINE
- TECHNICAL PROGRESS
- FULL-UP PROGRAM
- Δ WITH AUGMENTED PROGRAM
- ISSUES/CONCERNS
- CONCLUDING REMARKS

CSTI HIGH CAPACITY POWER

- PROVIDE FOR INCREASED POWER, RELIABILITY AND LIFETIME FOR NUCLEAR SPACE POWER SYSTEMS USING THE SP-100 REACTOR, THROUGH ADVANCED TECHNOLOGY DEVELOPMENT IN STATIC AND DYNAMIC ENERGY CONVERSION SYSTEMS, THERMAL AND POWER MANAGEMENT SYSTEMS AND MATERIALS

ITP-RJS91-001.3



SURFACE SYSTEMS/OPERATIONS
HIGH CAPACITY POWER *

OBJECTIVES

- Programmatic
Develop and Demonstrate Low Mass, Reliable Long-Lived Power Conversion Technology for Space Nuclear Reactor Power Systems
- Technical
Temperature - 1050K Stirling
 - 1300K Stirling and Thermoelectric

Power - Stirling at 25 kWe/Cyl - 50 kWe Modules
Lifetime - > 7 years

SCHEDULE

- 1992 - EOIM-3, STS-46 Flight Experiment
- 1993 - Thermoelectric Multicouple, Z = .85
- 1993 - Stirling, 1050K, 25 kWe/Cylinder, 25% eff.
- 1993 - H₂O Heat Pipe/Radiator Module Demo
- 1994 - 600K Radiator Segment Demo
- 1995 - Mfg. Specs. for Z = 1.0 Thermoelectric
- 1996 - Stirling, 1050K, 25 kWe/Cylinder, 30% eff.
- 1997 - Endurance Test, 1050K Stirling
- 1999 - Stirling, 1300K, 25 kWe/Cylinder, 15% eff.

<u>RESOURCES (\$M)</u>	<u>CURRENT</u>	<u>STRATEGIC</u>	<u>CoF</u>
• 1991	10.4	10.4	0
• 1992	10.6	10.6	0
• 1993	4.5	11.1	0
• 1994	4.6	16.8	0
• 1995	4.8	23.0	6.0
• 1996	5.0	30.5	5.0
• 1997	5.2	23.0	0
• 1998	-	-	5.0
• 1999	-	-	10.0

PARTICIPANTS

- Lewis Research Center
Responsibility for Project Lead
- Jet Propulsion Laboratory
Responsibility for Thermoelectrics

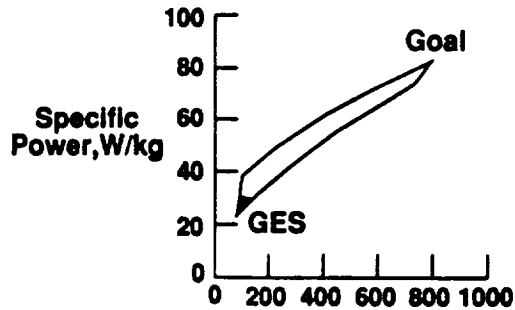
* Note: This Element is Integrated With Development of the SP-100 Space Nuclear Reactor Program

ITP91-002.2

POWER TECHNOLOGY DIVISION

SPACE NUCLEAR POWER

High Capacity Power



- Free piston Stirling converters
- Advanced thermal management
- Power management & distribution
- Environmental interactions
- Thermoelectrics
- Materials development

CD-98-10891

AEROSPACE TECHNOLOGY DIRECTORATE



HIGH CAPACITY POWER

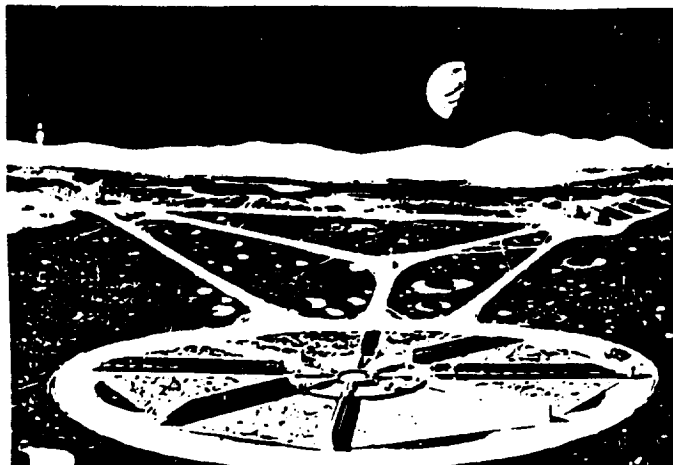
NASA

WHY NUCLEAR STIRLING ?

NUCLEAR-STIRLING IS AN ENABLING TECHNOLOGY PROVIDING LOW MASS, HIGH SPECIFIC POWER ELECTRICAL GENERATING SYSTEMS FOR THE MOON AND MARS

LUNAR BASE POWER SYSTEM IMLEO COMPARISON

- SAVES 1300 HLLVs vs SOA SOLAR PV
- SAVES 16 HLLVs vs ADVANCED SOLAR PV
- REQUIRES ONLY 1 LTV TO LUNAR SURFACE



550 kWe NUCLEAR-STIRLING LUNAR POWER SYSTEM

JF791-001 4



MISSION APPLICATION

- HIGH CAPACITY POWER PROGRAM
 - SUPPORTS LUNAR/MARS BASE
 - NEP SCIENCE, CARGO
 - DYNAMIC SYSTEMS FOR SPACE PLATFORMS, DIPS
 - HEAT REJECTION FOR ALL APPLICATIONS
- PROVIDE GROWTH AND BACK-UP FOR SP-100
 - IMPROVED MATERIALS
 - LOWER TEMPERATURE
 - INCREASED LIFETIME

ITP RJ591-001 10



HIGH CAPACITY POWER



HIGH CAPACITY POWER BASELINE PROGRAM MAJOR MILESTONES

- | | |
|------------------------------|--|
| • FREE-PISTON STIRLING | • 1050 K, 25 kW/CYLINDER, 30% EFF, 7 YEAR LIFE
(PRESENT - 650 K, 12.5 kW/CYLINDER, 20% EFF, 1000 HR. LIFE) |
| • THERMOELECTRICS | • $Z = .85 \times 10^{-3} \text{ K}^{-1}$ MULTICOUPLES/CONDUCTIVELY COUPLED
(PRESENT - $Z = .67 \times 10^{-3} \text{ K}^{-1}$ MULTICOUPLES/RADIATIVELY COUPLED) |
| • THERMAL MANAGEMENT | • 500 - 550 K RADIATOR SEGMENT TEST - STIRLING COLD END
(PRESENT - PAPER DESIGNS, COMPONENT PRODUCED, NO RADIATOR TESTS) |
| • POWER MANAGEMENT | • RAD HARD, HIGH TEMP SEMICONDUCTOR AND MAGNETICS COMPONENTS
(PRESENT - RADIATION DEGRADES SEMICONDUCTORS, HIGH TEMPERATURE DEGRADES MAGNETS) |
| • SYSTEM DIAGNOSTICS | • FIBER OPTIC POWER SENSOR FLIGHT QUALIFIED
(PRESENT - POWER SENSORS EMI SENSITIVE, FIBER OPTIC CURRENT SENSOR BREAKTHROUGH) |
| • ENVIRONMENTAL INTERACTIONS | • MODELS/EXPERIMENTS DEMONSTRATING LUNAR/MARTIAN/SPACE PLASMAS COMPATIBILITY OF SPACE POWER SYSTEMS
(PRESENT - NO MODELS AVAILABLE - INITIAL EXPERIMENTS ON MARS ENVIRONMENT BEGINNING) |

JMW91-007 4

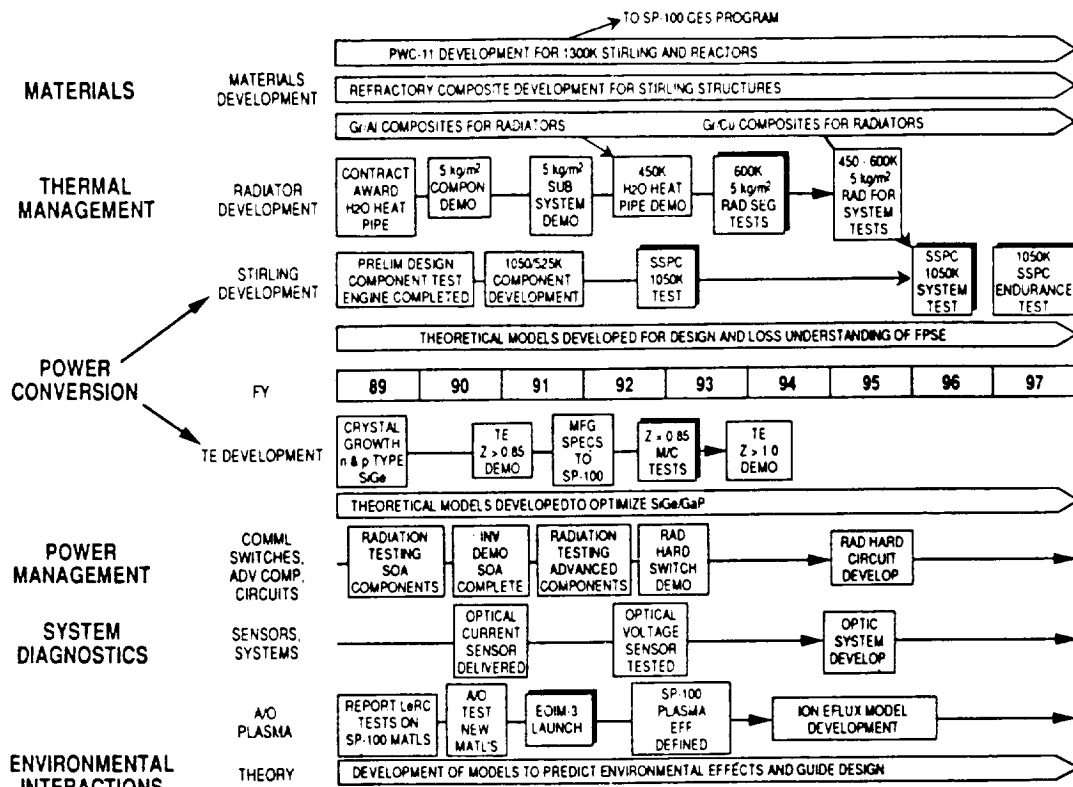
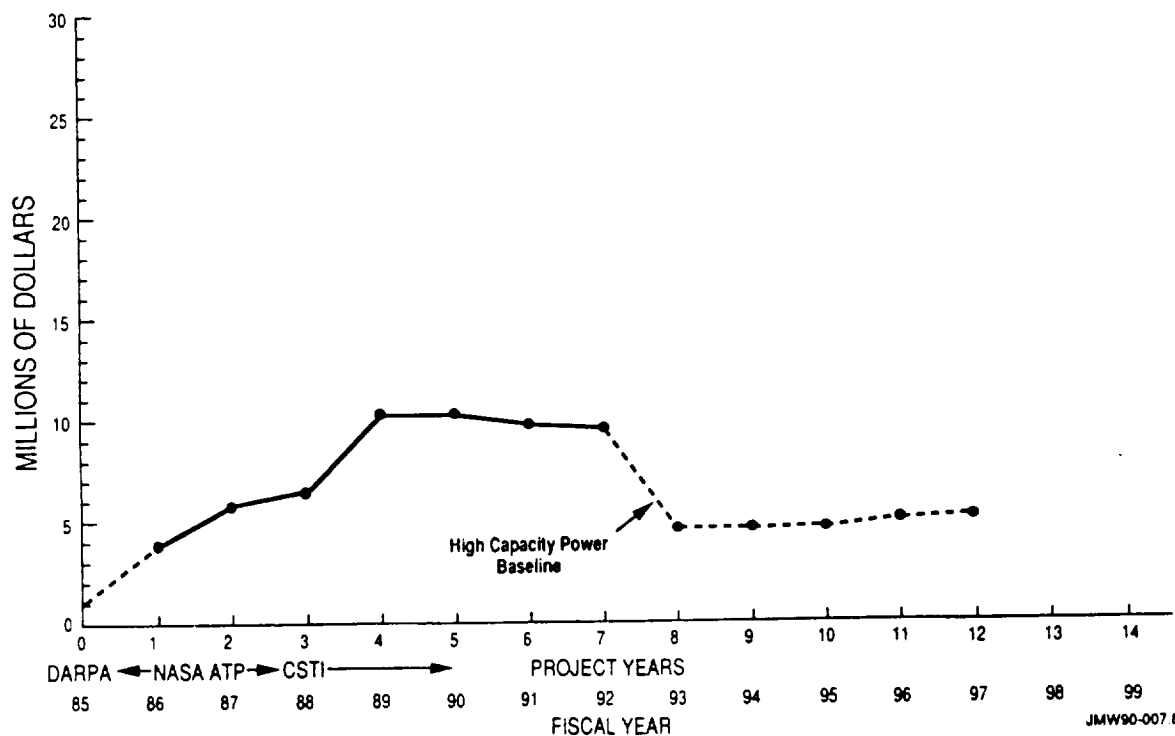


Figure 7

JMW90-004 2



NASA



JMW90-007 8



ADVANCED STIRLING

MAJOR OBJECTIVE:

DEMONSTRATE THE PERFORMANCE, SPECIFIC POWER, LIFETIME, RELIABILITY, OF A 25 kWe/PISTON, 1300 K, $T_R = 2$, FPSE FOR LUNAR BASE APPLICATION

- DEMONSTRATE PERFORMANCE OF SUB-SYSTEMS
(Heat Transport, Power Conversion, Heat Rejection, PMAD)
- INTEGRATE SUB-SYSTEMS/DEMONSTRATE SYSTEM OPERATION

ITP JMW91-001 2



CSTI HIGH CAPACITY POWER



SSPC SUPPORTING R&T

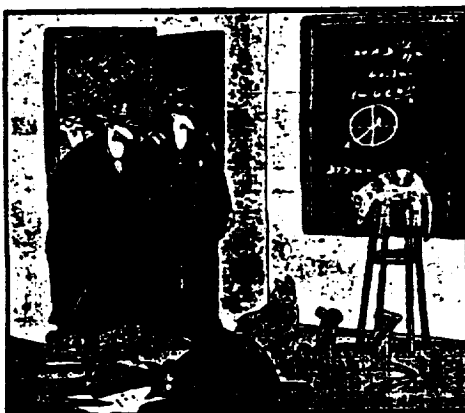
OBJECTIVE:

- TO ESTABLISH A STRONG FPSE TECHNOLOGY BASE

ACTIVITIES:

IN-HOUSE ENGINES

- SPRE
- RE-1000 HEAT PIPE
- RE-1000 HYDRAULIC
- SPIKE
- 1.5 kWe SOLAR DYNAMIC DESIGN



Notice all the computations, theoretical scribbles and lab equipment, Norm. . . . Yes, curiosity killed these cats

JED90-002 6

ANALYSIS

- CODE DEVELOPMENT
HFAST, GLUMPS, CFD
- LOSS UNDERSTANDING
CONTRACTS (3)
GRANTS (8)
ANNUAL WORKSHOP
- PARTICIPANTS
U. OF MINNESOTA (3)
CLEVELAND STATE (2)
MIT
U. OF PITTSBURGH
CASE-WESTERN RESERVE
SUNPOWER
MTI
GEDEON ASSOCIATES
NASA-LeRC

COMPONENT TECHNOLOGY

- MAGNETICS
- LINEAR ALTERNATORS
- CONTROLS
- LOAD INTERACTION
- HEAT PIPES
- HEAT EXCHANGERS
- MATERIALS/JOINING
- MAGNETIC BEARINGS
- HIGH TEMPERATURE INSTRUMENTATION



FREE-PISTON STIRLING ENGINES

KEY PROGRAM ELEMENTS

SCALING: 12.5 → 25 kWe/P

SPECIFIC MASS: 9 kg/kWe < 6 kg/kWe

EFFICIENCY: 20 → 30 (35)

LIFETIME: ≥ 7 YEARS

OPERATING TEMPERATURE: 650 K → 1050 K (1300 K)

APPROACH

COMPONENT DEV. TESTING → SUB-SYSTEMS → SYSTEM TESTS

STRONG AS SUPPORTING ANALYSIS

ITP RJ591-001.5



HIGH CAPACITY POWER STIRLING DEVELOPMENT BASELINE PROGRAM

NASA

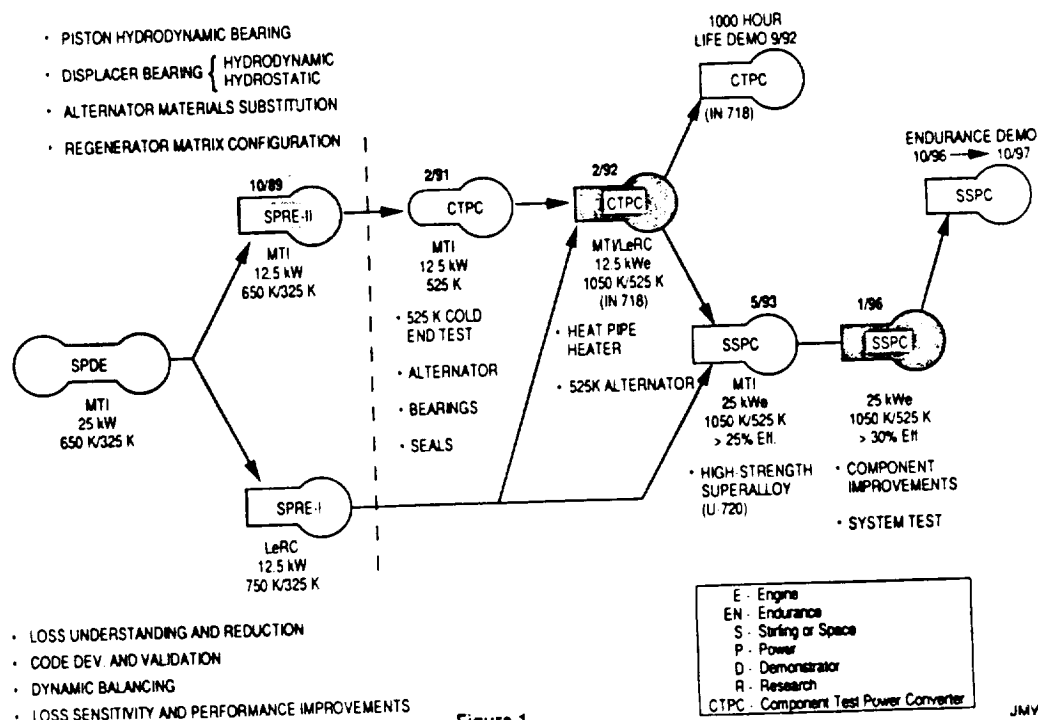


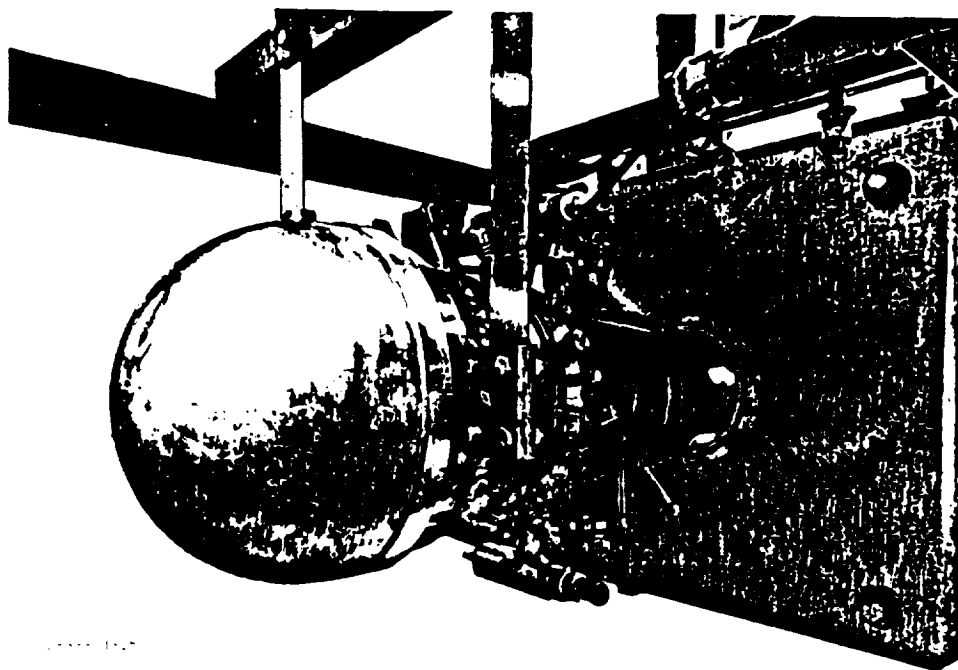
Figure 1

PT8-7

JMW90-005.7

QUALITY
OF WORK

FREE-PISTON STIRLING SPACE POWER RESEARCH ENGINE

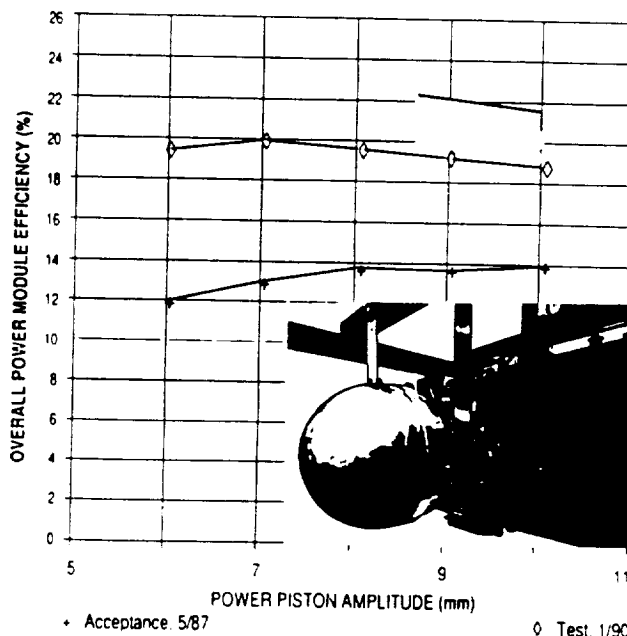
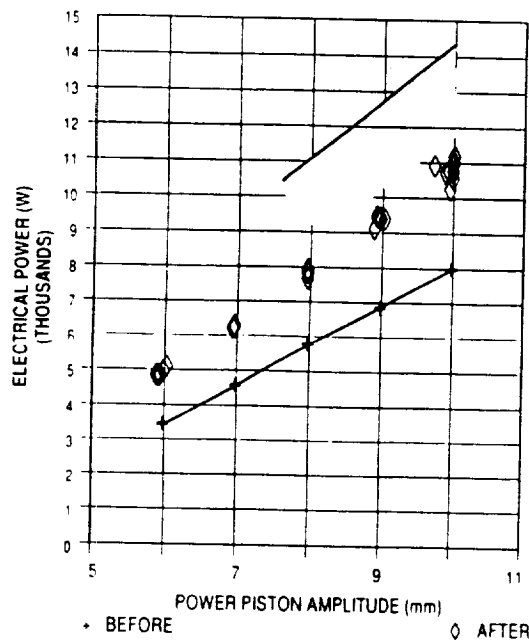


HIGH CAPACITY POWER

NASA

SPRE TEST

150 Bar, $T_{HOT} = 650$ K, $TR = 2.0$





HIGH CAPACITY POWER

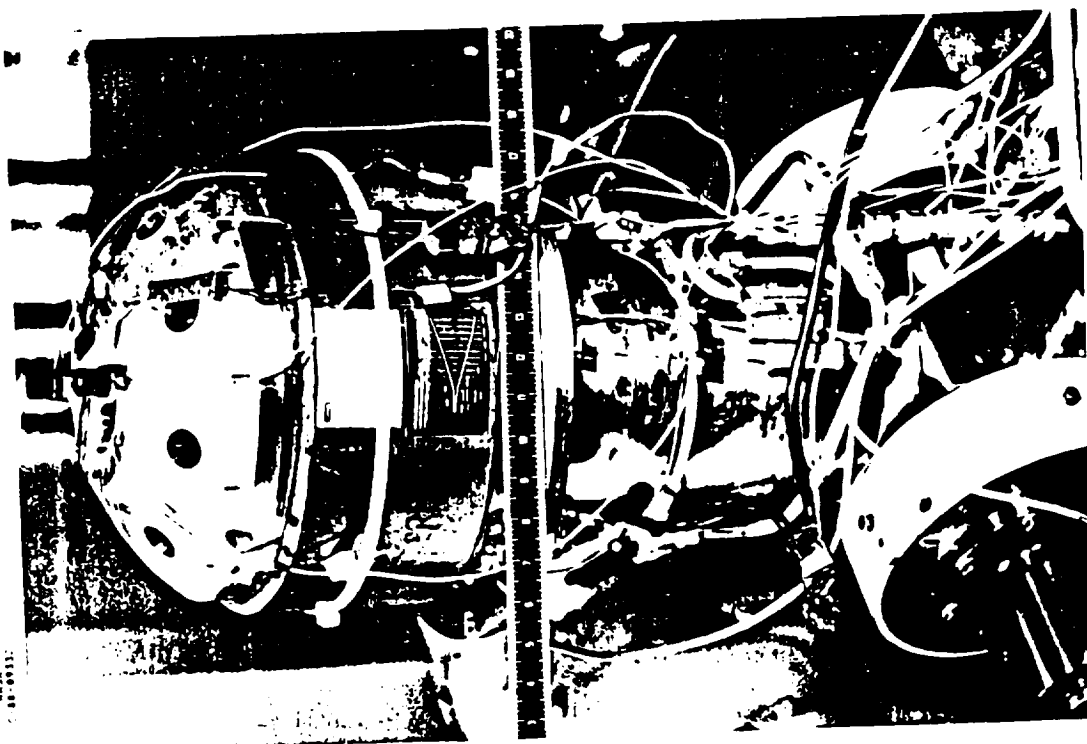
NASA

SPRE TECHNICAL PROGRESS

• SUCCESSFUL DEMONSTRATION OF:

- 12.5 kWe/PISTON
- $T_R = 2$
- NON-CONTACTING GAS BEARINGS (HYDROSTATIC & HYDRODYNAMIC)
- STABLE OPERATION WITH CENTERING PORTS REDUCED FROM 6 TO 2
- RADIAL CLEARANCE INCREASED FROM 2 mils TO 5 mils
 - PREDICTED POWER LOSS
 - NO CHANGE IN EFFICIENCY
- VALIDATED DESIGN CODES
- DEMONSTRATED LINEAR ALTERNATOR EFFICIENCY > 90% AT 325 K

ITP JMW91-001.9





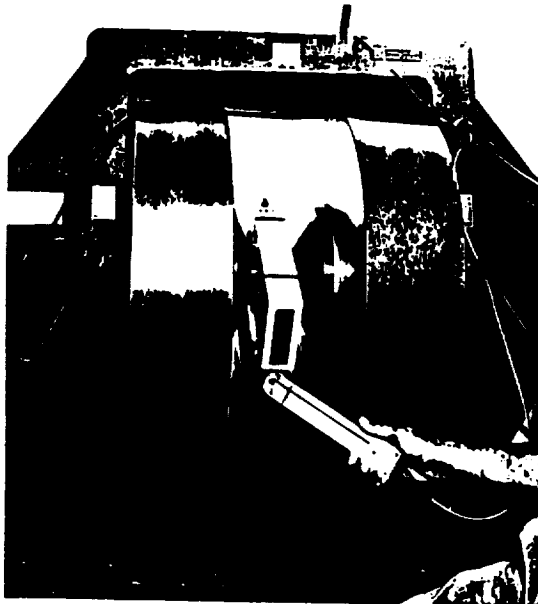
LINEAR ALTERNATOR TECHNICAL PROGRESS

- LINEAR ALTERNATOR DYNAMOMETER QUANTIFIED EDDY CURRENT LOSSES
 - VERIFIED IMPROVED PERFORMANCE WITH NON-MAGNETIC SUPPORT STRUCTURE
- LINEAR ALTERNATOR "SHAKE AND BAKE" TEST RIG VALIDATES INSULATION AND STRUCTURAL INTEGRITY

ITP JMW91-001 10

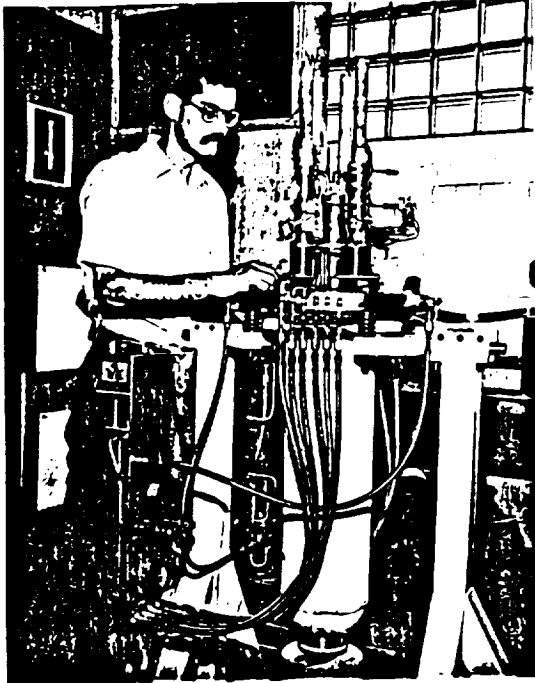


HIGH TEMPERATURE MAGNETICS TECHNICAL PROGRESS



- 5 COMMERCIAL MATERIALS EVALUATED
- SAMARIUM₂ COBALT₁₇ CHOSEN FOR 525K
- DEFINES DESIGN MARGINS ON TEMPERATURE AND CURRENT
- STABILITY - CYCLING AND LIFETIME UNDER INVESTIGATION

FREE-PISTON STIRLING ENGINE ADVANCED HEAT EXCHANGER TESTS



- MEASURED HEAT PIPE TEMPERATURE DROPS AGREE WITH THE ANALYTICAL PREDICTIONS
- OPERATED WITH HEAT PIPE TEMPERATURE AS HIGH AS 1050K
- HEATER METAL AND GAS TEMPERATURE PROFILES ARE BEING STUDIED TO BETTER UNDERSTAND HEAT FLUX DISTRIBUTION
- HEAT EXCHANGERS WILL BE CHARACTERIZED WITH HEAT PIPES OPERATING WITH GRAVITY AND AGAINST GRAVITY



HIGH CAPACITY POWER

NASA

WE HAVE DEMONSTRATED

12.5 kWe/PISTON

EFFICIENCY = 20%

$T_R = 2.0$

$\frac{T_H = 650 \text{ K}}{T_C = 325 \text{ K}}$

**DATA, ANALYSIS PROVIDE CONFIDENCE TO
PROCEED TO THE NEXT GENERATION ENGINE**



STIRLING SPACE POWER CONVERTER PROGRAM

PHASE TWO 1050K SUPERALLOY COMPONENT TEST POWER CONVERTER (CTPC)

OBJECTIVE:

TO PROVIDE A LOW-COST, LOW-RISK AND SHORT SCHEDULE APPROACH
TO DEVELOP ALL COMPONENT TECHNOLOGIES FOR THE 25 kWe 1050 K
SUPERALLOY STIRLING SPACE POWER CONVERTER

PROGRAM GOALS:

- END OF LIFE POWER - 25 kWe
- EFFICIENCY - > 25% @ $T_r = 2.0$
- LIFE (DESIGN) - 60,000 HOURS
- VIBRATION - < .04 mm (OPPOSED PISTON)
- BEARINGS - NON CONTACTING (GAS FILM)
- SPECIFIC MASS - < 6 kg/kWe
- HOT END - HEAT PIPE

JED91-002.3

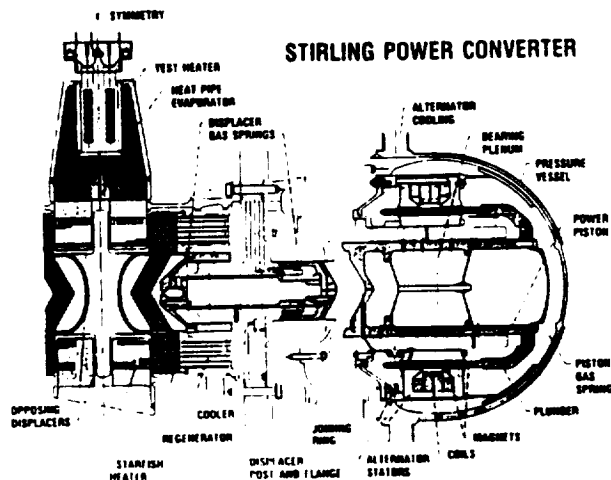


STIRLING SPACE POWER CONVERTER PROGRAM PHASE TWO

1050 K SUPERALLOY COMPONENT TEST POWER CONVERTER (CTPC)

FIRST MOTORING TEST OF COLD END

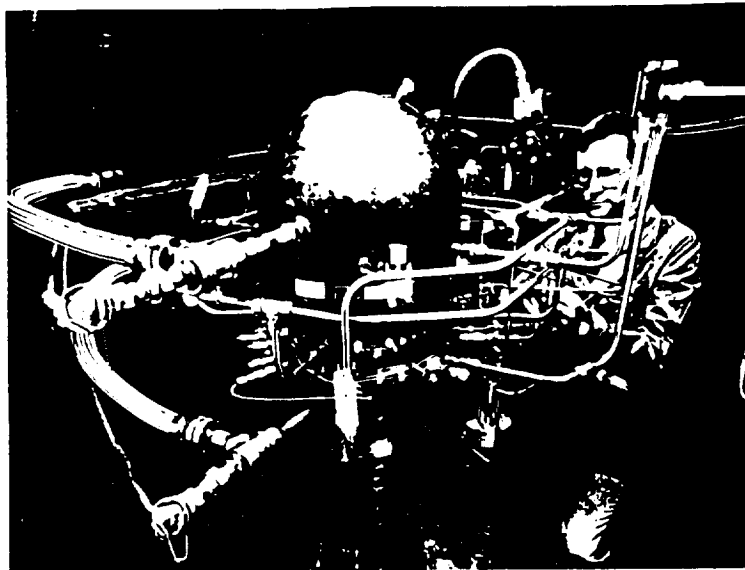
- 12.5 kWe DESIGN
- MOTORED AT 70 Hz (4/15/91)
- "NEW" HYDROSTATIC BEARING SYSTEM
- NO RUBS
- START OF MT/CTPC TEST PROGRAM



JED 91 002.3

COMPONENT TEST POWER CONVERTER (CTPC)

COLD END MOTORING TEST



HIGH CAPACITY POWER

NASA

WILL IT REALLY WORK IN SPACE?

STIRLING MACHINES (CRYOCOOLERS) HAVE ALREADY FLOWN IN SPACE

- 7 FLIGHTS HAVE BEEN IDENTIFIED (6 USA/1 USSR)
- DEMONSTRATED OPERATION FROM HOURS TO 6 YEARS
- KINEMATIC STIRLING TECHNOLOGY
 - * STIRLING CRYOCOOLER PROTOTYPES DESIGNED FOR TERRESTRIAL APPLICATION



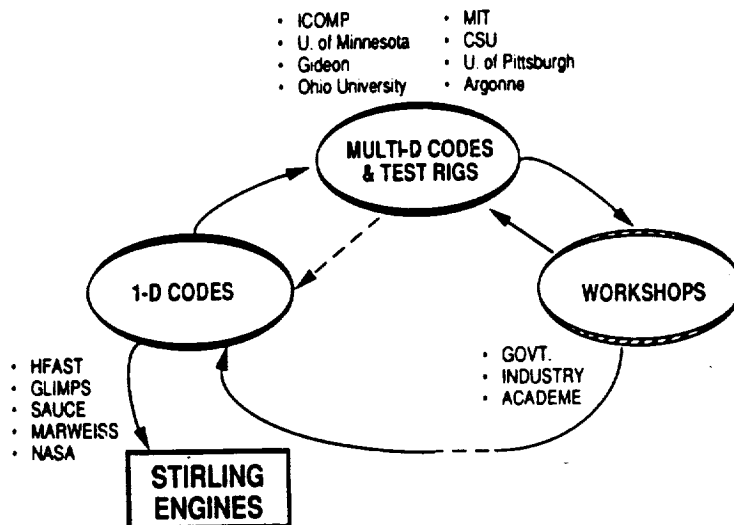
PLANNED LONG-LIFE CRYOCOOLER MISSIONS - FREE-PISTON STIRLING TECHNOLOGY

- 7 FLIGHTS PLANNED WITH FLEXURE BEARING SYSTEM
 - ALONG TRACK SCANNING RADIOMETER - 1991
 - IMPROVED STRATOSPHERIC AND MESOSPHERIC SOUNDER - 1991
 - HIGH TEMPERATURE SUPERCONDUCTIVITY EXPERIMENT - 1992
 - X-RAY SPECTROMETER - 1996
 - EARTH OBSERVING SYSTEM INSTRUMENTS - '96, '97, '98
- 1 FLIGHT PLANNED WITH GAS BEARING SYSTEM
 - SDI/SPAS EXPERIMENT 1994
 - * TO DEMONSTRATE THAT FREE-PISTON STIRLING CRYOCOOLERS WITH GAS BEARINGS CAN SURVIVE LAUNCH ENVIRONMENTS

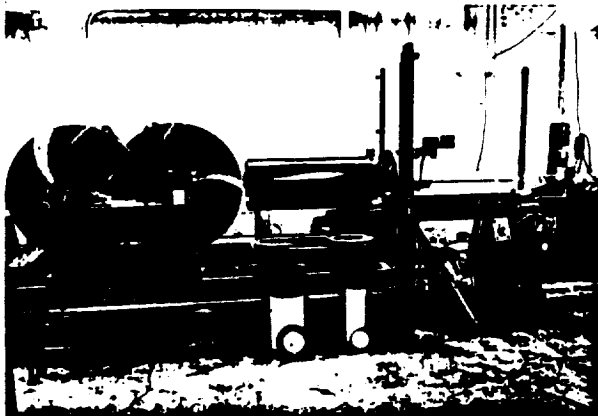


NASA

- IMPROVED UNDERSTANDING OF FLUID FLOW AND HEAT TRANSFER IN HEATERS, COOLERS, AND GAS SPRINGS WITH OSCILLATING FLOW
- MULTI-DIMENSIONAL CODES → INSTANTANEOUS HEAT TRANSFER AND FLUID FRICTION COEFFICIENTS FOR 1-D DESIGN CODES



ITP JMW91-001.12



OSCILLATING-FLOW RIGS

MINNESOTA

OHIO U.

MIT



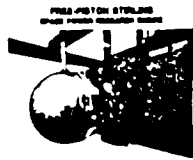


CSTI HIGH CAPACITY POWER

NASA
Lewis Research Center

GOVERNMENT IN-HOUSE TEST FACILITIES

SPACE POWER RESEARCH ENGINE



STIRLING RE 1000
HEAT PIPE TEST



LINEAR ALTERNATOR RESEARCH



ATOMIC OXYGEN TEST



125 TON VACUUM HOT PRESS



HIGH TEMPERATURE VACUUM
CREEP TEST



HEAT PIPE TEST



HI-TEMP CALORIMETRIC
VACUUM EMISSOMETER



CD-89-41441



CSTI HIGH CAPACITY POWER

NASA
Lewis Research Center

INDUSTRY/UNIVERSITY TEST FACILITIES

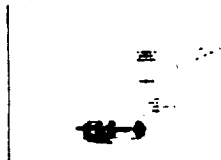
MTI MANUFACTURING



U. OF PGH. HIGH TEMPERATURE
MAGNETIC TEST



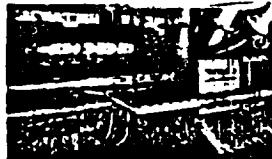
CWRU ATOMIC OXYGEN TEST



MTI FREE-PISTON STIRLING



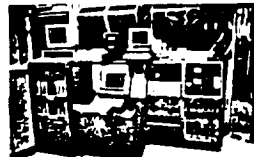
OHIO STATE UNIVERSITY
MATERIAL TEST REACTOR



SUNPOWER OSCILLATING/STEADY-
STATE FLOW TEST



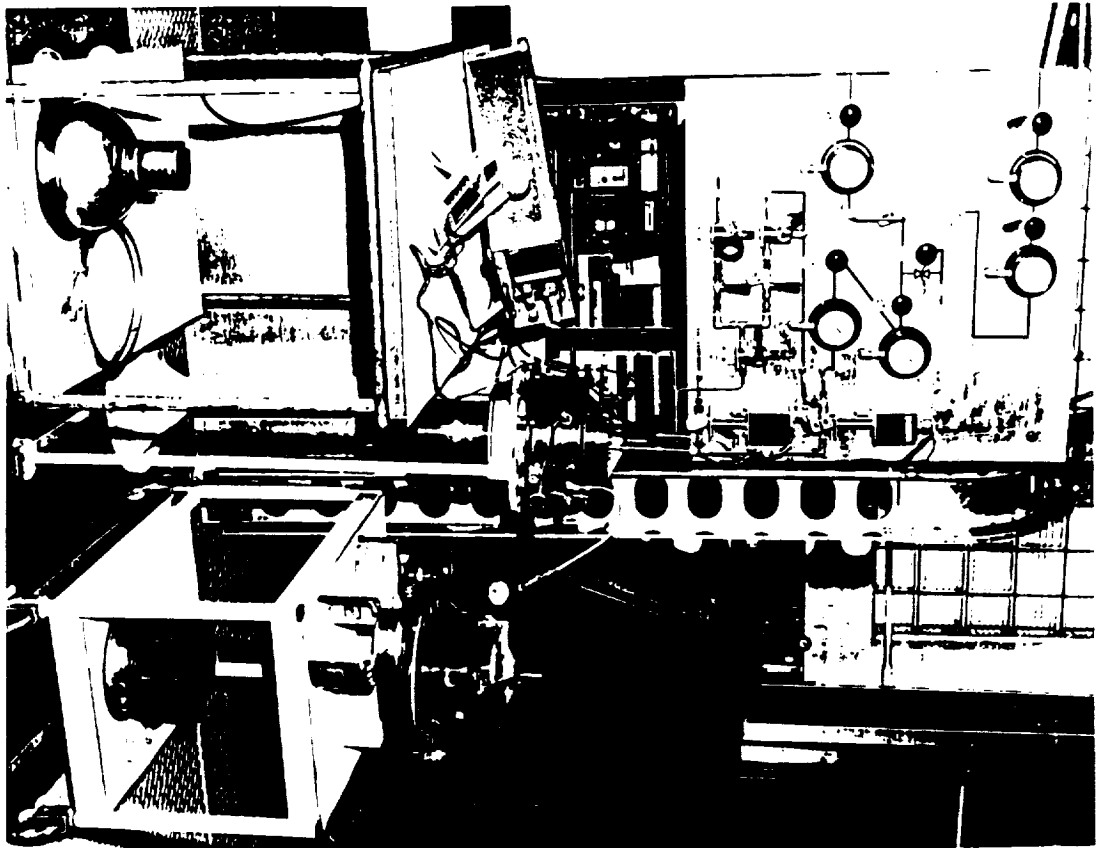
MTI LINEAR ALTERNATOR
DEVELOPMENT



UNIVERSITY OF CINCINNATI
GAMMA TEST



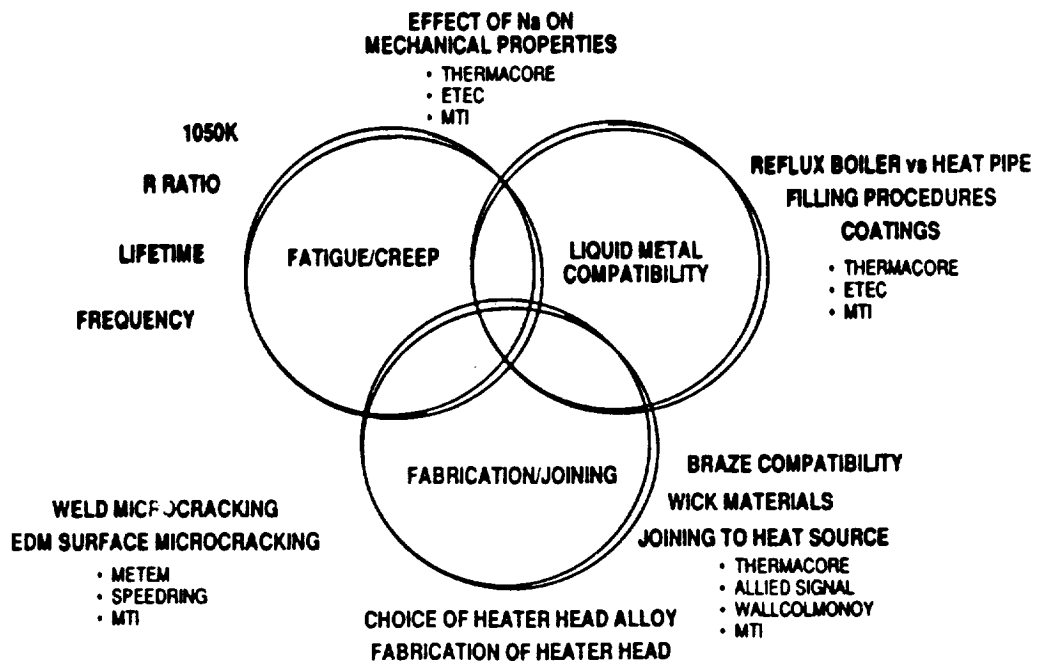
CD-89-41442



CSTI HIGH CAPACITY POWER

NASA

MATERIALS STUDIES FOR THE STIRLING SPACE POWER CONVERTER



JED88-802 41



SODIUM HEAT PIPE FATIGUE TESTS
THERMACORE MTI



- SIMULATES STARFISH HEATER LOADINGS AND ENVIRONMENT
 - SODIUM HEAT PIPE
 - INCONEL 718 (CTPC MATERIAL)
 - EVALUATES CORROSION EFFECTS
 - EVALUATES CREEP AND HIGH CYCLE FATIGUE
- 4 HEAT PIPES FABRICATED
 - 1 CUT APART FOR O₂ TEST
 - EVALUATED 100 PPM
 - MATERIAL 1000 PPM
 - 3 INSTALLED IN FATIGUE TEST RIG
- ETEC PUMPED LOOP IDENTIFIED AS SUITABLE FILL TECHNIQUE

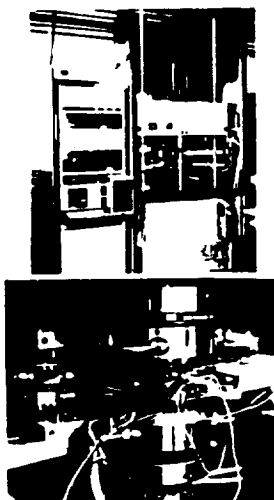
NASA
C-90-07868

National Aeronautics and
Space Administration
Lewis Research Center

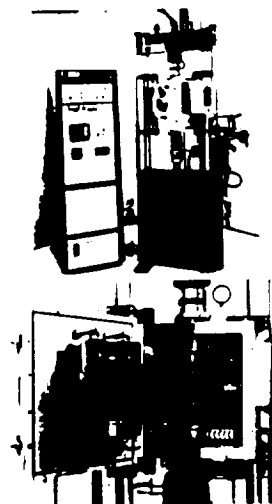
AEROSPACE TECHNOLOGY DIRECTORATE

NASA

**BASE TEST SYSTEMS CAN BE EASILY UPGRADED
TO TEST REFRACTORY METALS**



From superalloys
base test system



To refractory metal upgrade
of base test system

CD-90-48247



HIGH CAPACITY POWER

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STIRLING MATERIALS PROGRESS

- CERAMIC COATINGS - MAGNET INSULATORS
- NON-MAGNETIC ALTERNATOR SUPPORT STRUCTURES
- REFRACTORY MATERIALS - 1300 K CONVERTER
- STEM AND EDM TECHNIQUES - HOT END MATERIALS
- TRANSIENT LIQUID PHASE DIFFUSION BONDING
EB WELDING } UDIMET 720
- LOW OXYGEN FILL TECHNIQUES - Na HEAT PIPES
- VISCOPLASTIC/INELASTIC ANALYSIS & TESTING - LONG LIFE DESIGN

ITP-JMW91-001 14



HIGH CAPACITY POWER

NASA

STIRLING SYSTEMS PROGRESS

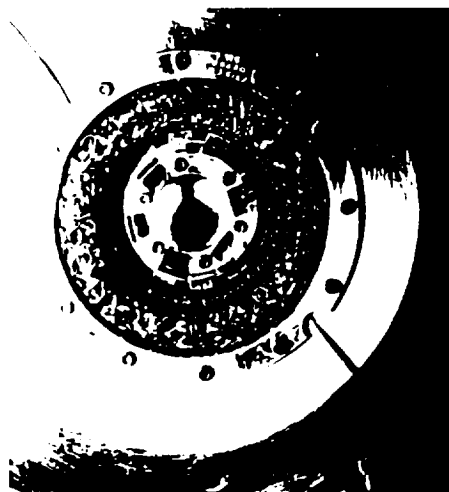
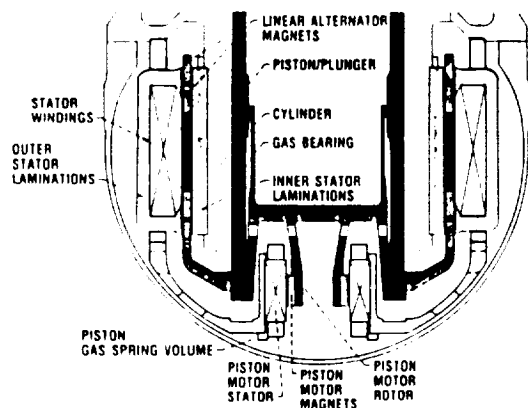
- LUNAR BASE REFRACTORY STIRLING-NUCLEAR INTERFACE CONCEPTS
- SYSTEM RESPONSE TRANSIENTS
- MULTIPLE CONVERTER INTEGRATION & INTERACTION

ITP-JMW91-001 13



**SPIN-MOTOR FOR PISTON-CYLINDER
HYDRODYNAMIC GAS BEARING
(DEMONSTRATED ON SPRE)**

SCHEMATIC SHOWING PISTON SPIN-MOTOR FOR
PISTON-CYLINDER HYDRODYNAMIC GAS BEARING
CONCEPT FOR A FREE-PISTON STIRLING ENGINE



ITP JMW91-001 15



NON-CONTACTING BEARINGS TECHNOLOGY PROGRESS

- HYDROSTATIC BEARING LOSSES REDUCED 50%
- HYDRODYNAMIC BEARING DEMONSTRATED
- "NEW" HIGH STIFFNESS, ULTRA STABLE HYDRODYNAMIC BEARING IDENTIFIED
- MAGNETIC BEARINGS VIABLE FOR HIGH POWER CONVERTERS
- OTHER NON-CONTACTING BEARINGS UNDER INVESTIGATION

ITP JMW91-001 15



HIGH CAPACITY POWER

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REFERENCE ENGINE DESIGN GUIDING EFFORT

- NEW "RELATIVE DISPLACER" DESIGN REDUCES COMPLEXITY, IMPROVES MANUFACTURABILITY AND RELIABILITY, IMPROVES POWER AND EFFICIENCY (+2% POINTS)

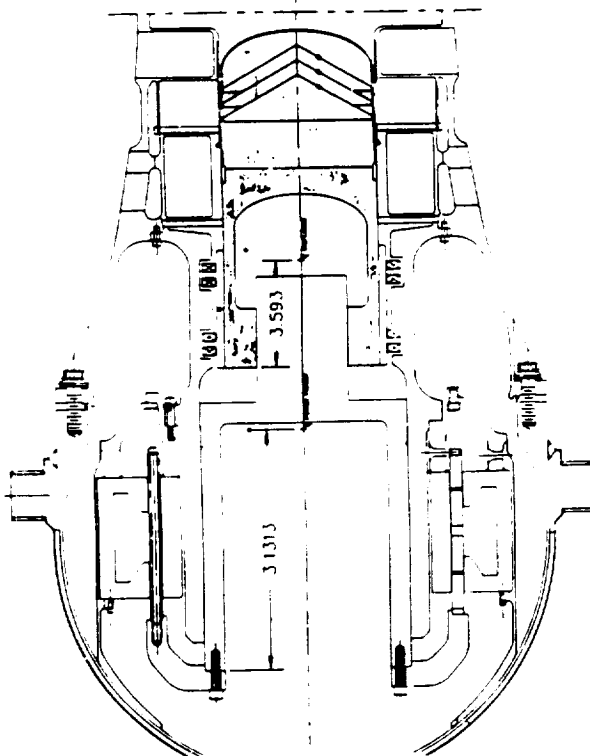
ITP JMW91-001.17



HIGH CAPACITY POWER

NASA

RSSE RELATIVE DISPLACER GAS SPRING CONFIGURATION



- REDUCED COMPLEXITY OF DISPLACER DRIVE
- IMPROVED MANUFACTURABILITY
- IMPROVED RELIABILITY
- ACCEPTS MAGNETIC BEARINGS
- INCREASED POWER DENSITY
- APPROACHES 30% EFFICIENCY

JED-900 03.3



ADVANCED THERMOELECTRICS

MAJOR OBJECTIVES:

DEVELOP SiGe/GaP n-LEG AND p-LEG TO PRODUCE THE $Z = .85 \times 10^{-3} \text{ K}^{-1}$ SPECIFIED FOR THE SP-100 REACTOR SYSTEM

- OPTIMIZE DOPANTS. ADD SCATTERING CENTERS
- DETERMINE MANUFACTURING SPECIFICATIONS
- PROCURE AND TEST MODULES/MULTICOUPLES FOR ACCELERATED LIFETIME MEASUREMENTS

ITP JMW91-001.3

THERMOELECTRIC DEVELOPMENT

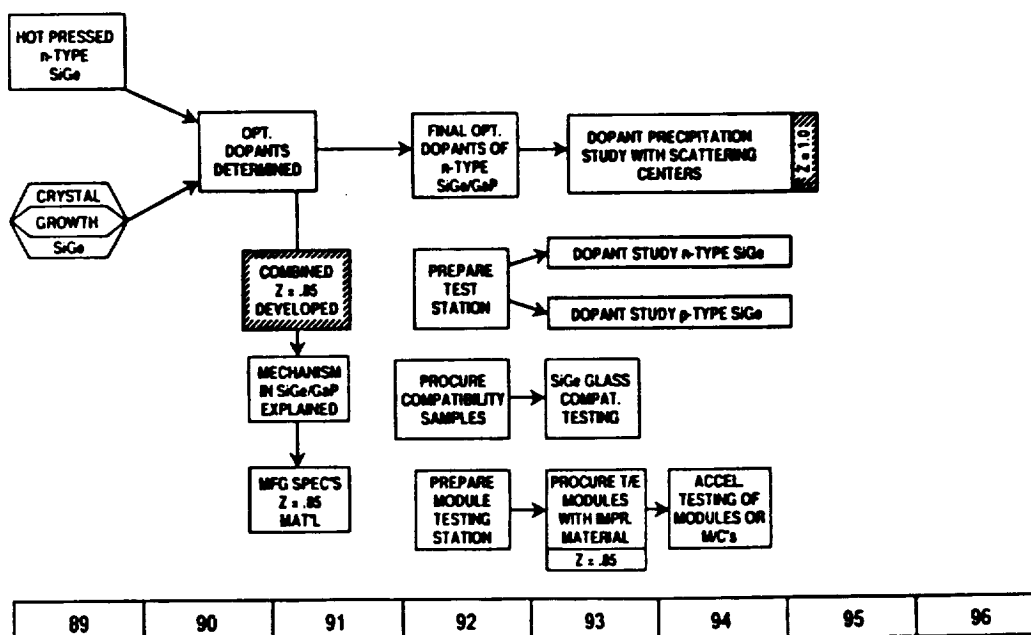
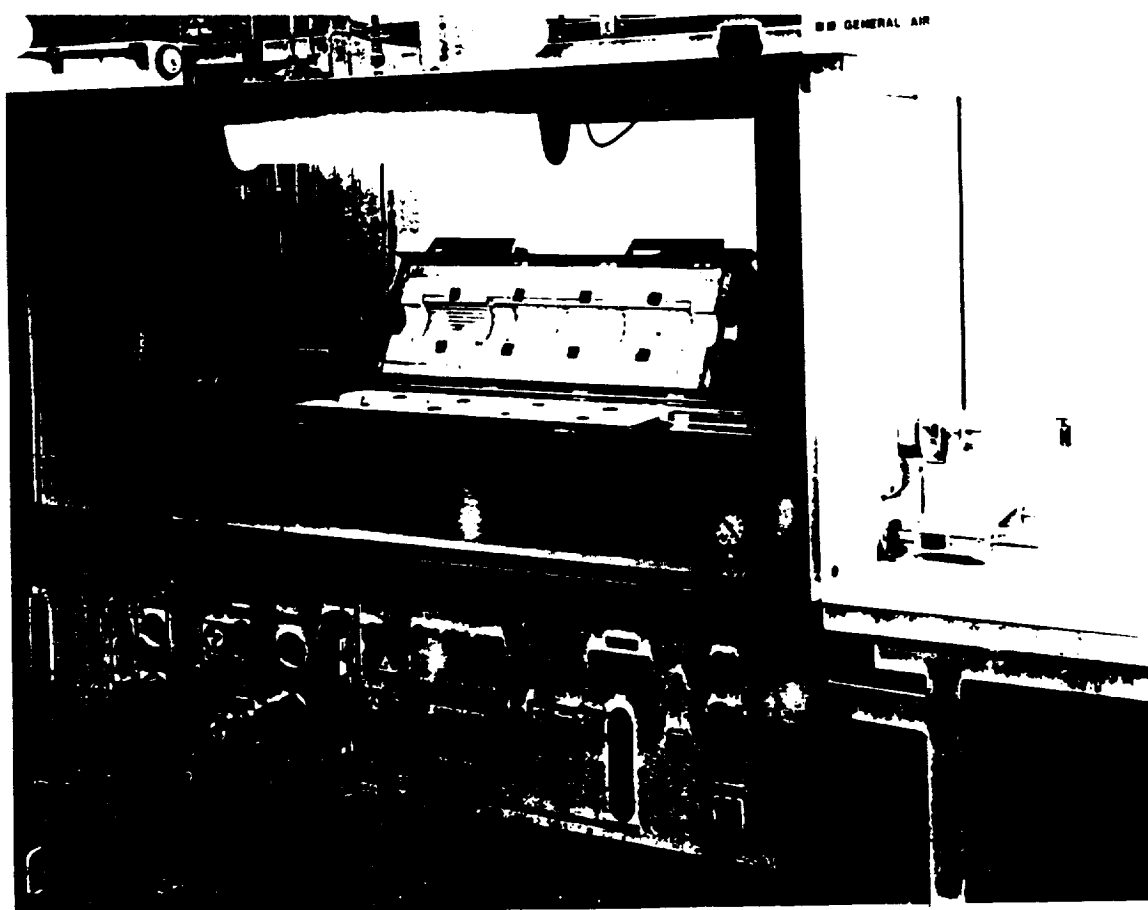
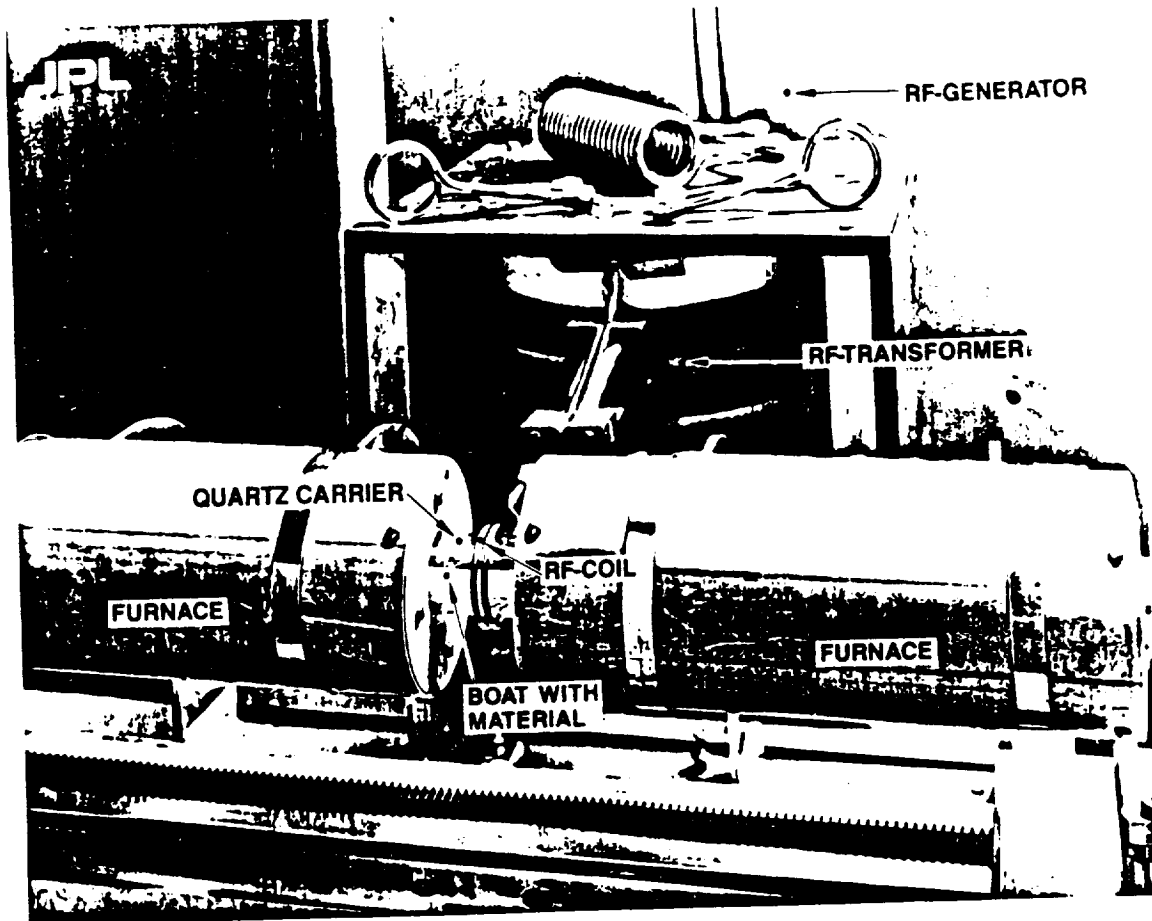


Figure 6

JMW90-004.3





ADVANCED THERMOELECTRICS - BASELINE PROGRAM

THERMOELECTRICS GOALS:

- REPRODUCIBLY OBTAIN n-TYPE SiGe/GaP with $Z = .9 - 1.0 \times 10^{-3} \text{ K}^{-1}$
 - ADD INERT SCATTERING CENTERS TO INCREASE Z TO $1.1 - 1.2 \times 10^{-3} \text{ K}^{-1}$
- INCREASE Z OF p-LEG TO $= .70 - .75 \times 10^{-3} \text{ K}^{-1}$ WITH SCATTERING CENTERS
 - RESULTS IN COMBINED Z TO $.85 - .90 \times 10^{-3} \text{ K}^{-1}$ BETWEEN $600 - 1000^\circ\text{C}$

PRESENT STATUS

N-LEG: 9 SAMPLES Z BETWEEN 0.85 AND $1.0 \times 10^{-3} \text{ K}^{-1}$

CANNOT FABRICATE HIGHEST Z SAMPLES AT WILL

CAN FABRICATE HEAVILY OVERDOPED SAMPLES, MUST REDUCE CARRIER CONCENTRATION

P-LEG: INCREASED Z $10 - 15\%$ ($.6 \times 10^{-3} \text{ K}^{-1}$) BY OPTIMIZING BORON CONTENT

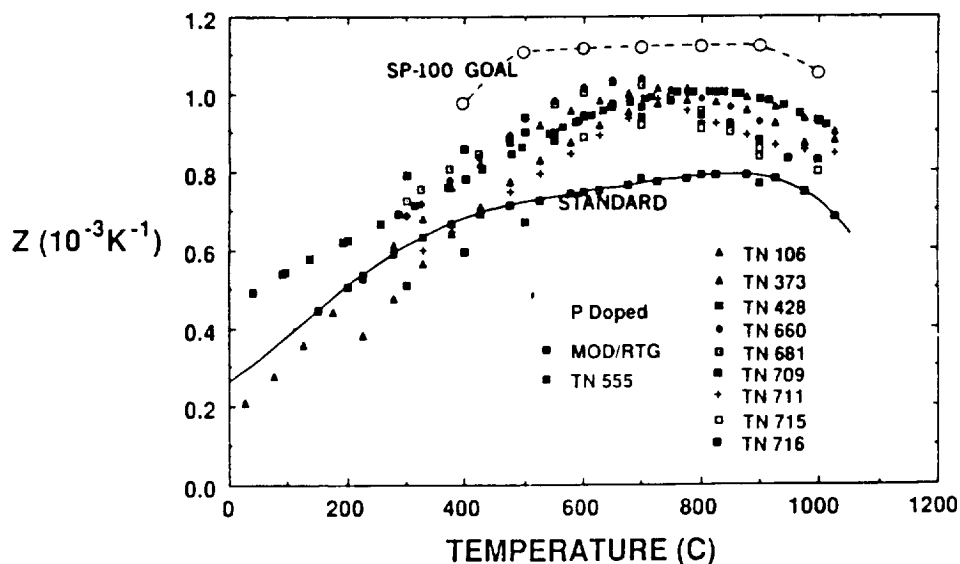
SMALL INERT PARTICLES BEING ADDED TO REDUCE THERMAL CONDUCTIVITY

MODEL PREDICTS Z INCREASE OF 40% POSSIBLE WITH PARTICULATE SCATTERING

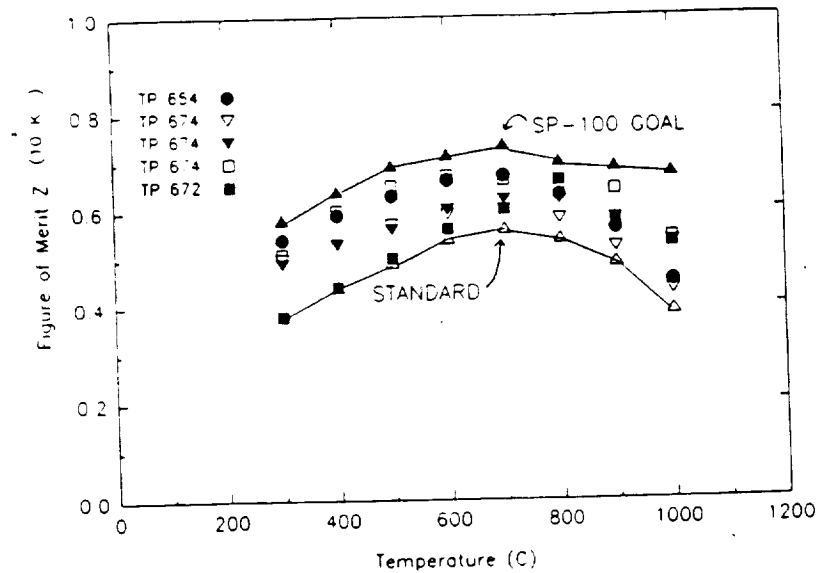
JMW91-007.5

JPL

IMPROVED n-TYPE SiGe/GaP

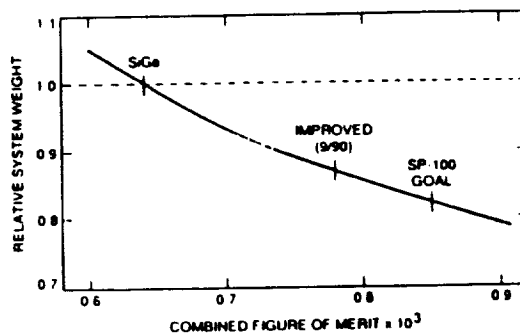
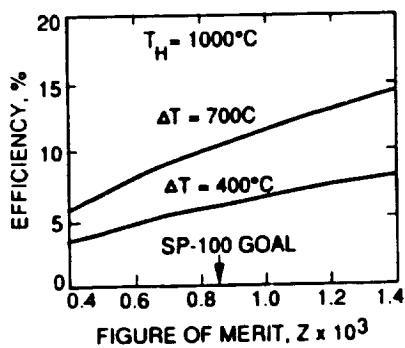


Z FOR p-TYPE SiGe



JPL
Los Alamos

OVERALL T/E IMPROVEMENT



• SP-100 GOAL OF $Z_{np} = 0.85$ (B.O.L.) IN SIGHT

CE 4
2/15/91



HIGH CAPACITY POWER THERMAL MANAGEMENT



MAJOR OBJECTIVES:

DEVELOP AND DEMONSTRATE ADVANCED THERMAL MANAGEMENT CONCEPTS
FOR BOTH THERMOELECTRIC AND STIRLING CONVERSION SYSTEMS

STIRLING - RADIATOR AT 475 - 600 K, 5 kg/m² , 10 YEAR LIFETIME, .99 RELIABILITY

- HOT SIDE HEAT EXCHANGERS AND PUMPS
 - Low Mass, High Performance, Superalloy and Refractory
- COLD SIDE HEAT EXCHANGERS AND PUMPS
 - Low Mass, High Performance

THERMOELECTRIC - RADIATOR AT 800 - 900 K, 5 kg/m² , 10 YEAR LIFETIME,
.99 RELIABILITY

DEMONSTRATE PERFORMANCE OF SUB-SYSTEMS (Heat Pipes, Pumps,
Heat Exchangers)

INTEGRATE RADIATOR SEGMENTS AND OTHER SUB-SYSTEMS INTO
STIRLING SYSTEM TEST AT 1050K (1997) AND 1300K (1999)

ITP JMW91-001 4



EXPLORATION TECHNOLOGY

THERMAL MANAGEMENT

PROJECT KEY ELEMENTS

ADVANCED RADIATOR SEGMENT DEVELOPMENT

- TECHNOLOGY → COMPONENT → SUBSYSTEM → RADIATOR SEGMENT
 - 875 K HEAT PIPE WITH FINS FOR THERMOELECTRIC
 - 600 K LiNaK PUMPED LOOP FOR STIRLING
- SURFACE MORPHOLOGY
 - EMISSIVITY >.85 WITH SURFACE TREATMENT, NO COATINGS
- MATERIALS DEVELOPMENT
 - Cu/Gr COMPOSITE TO REPLACE Be FINS WITHOUT MASS PENALTY
- HEAT PIPE/RADIATOR DESIGN CODES AND CORRELATION
 - ANALYSIS, AUDITS, TRANSIENT BEHAVIOR
 - TESTING



THERMAL MANAGEMENT BASELINE BUDGET

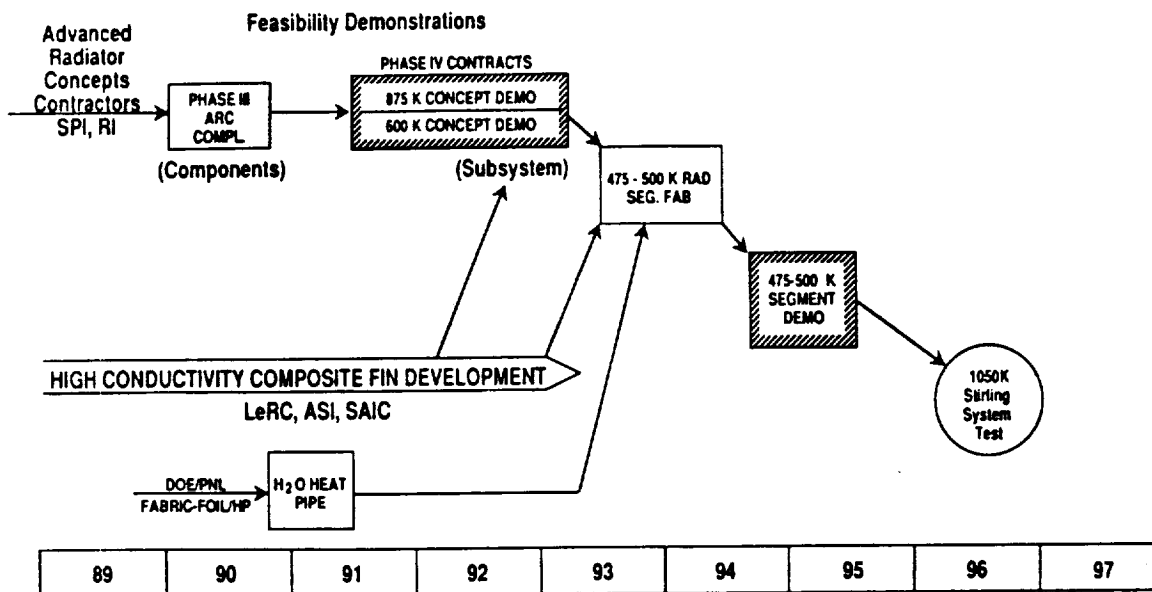
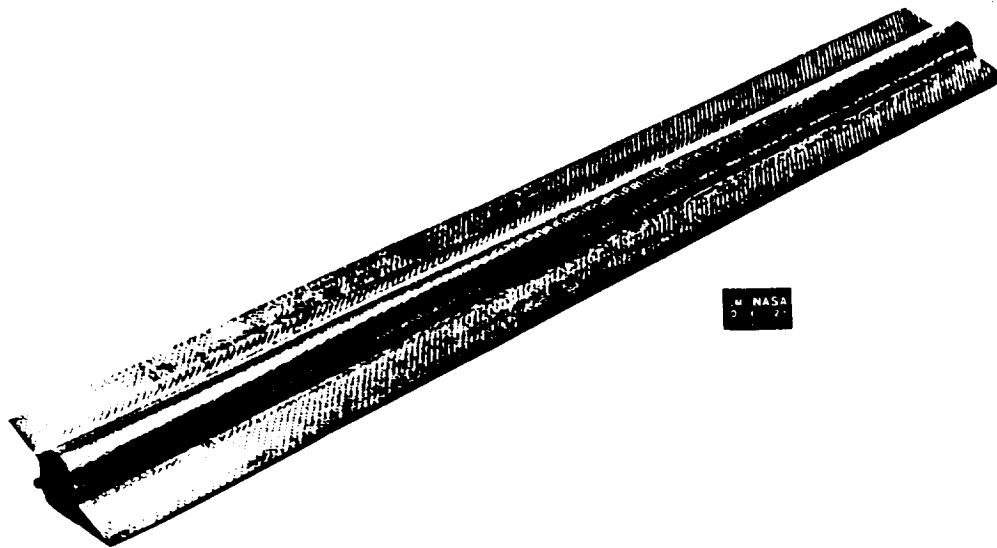


Figure 9

JMW90-004.4



HIGH CAPACITY POWER



ROCKWELL ACCOMPLISHMENTS

- DEMONSTRATED CARBON-CARBON COMPOSITE INTEGRATED TUBE-FIN MANUFACTURING TECHNOLOGY
- IDENTIFIED Nb AND Ti AS LINER OR COATING MATERIALS TO CONTAIN WORKING FLUID
- IDENTIFIED BRAZE MATERIALS AND Re PRECOAT FOR JOINING LINERS TO TUBES (PERFORMED INITIAL BRAZING AND COATING EXPERIMENTS)
- INITIATED TWO ALTERNATIVE METAL FOIL LINER FABRICATION SUBCONTRACTS



LOW TEMPERATURE Li-NaK RADIATOR EXPERIMENTAL TEST SECTION

Operated In Li-NaK Loop

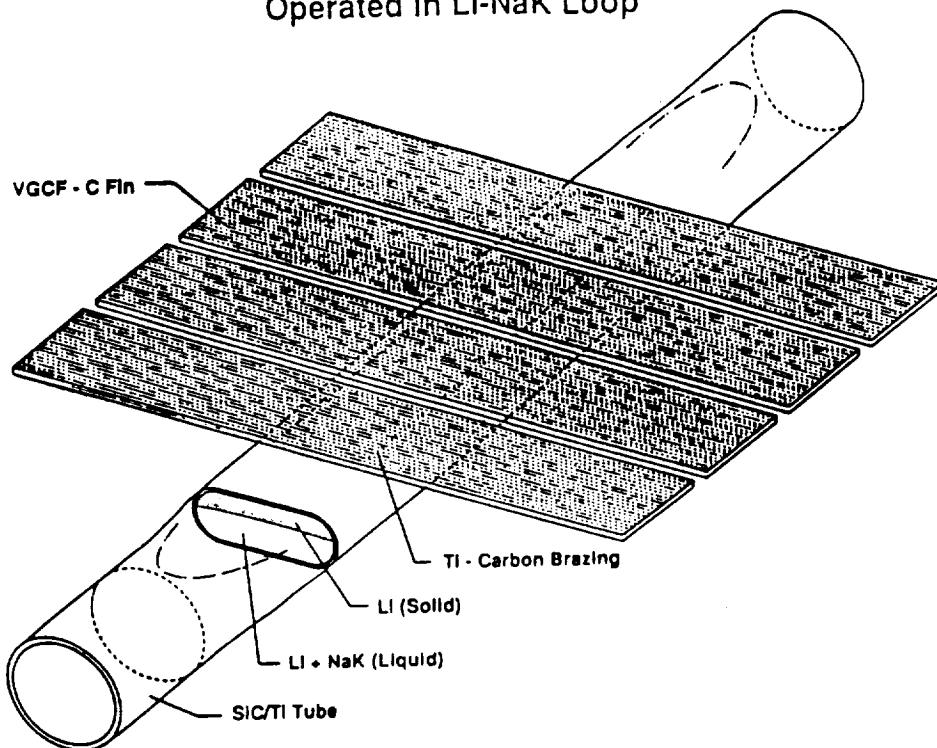


FIGURE 1

C9-29C



HIGH CAPACITY POWER

NASA

SPI ACCOMPLISHMENTS

- COMPLETE Li/NaK LOOP GROUND TEST FACILITY
- PERFORMED Li/NaK FLOW TESTS IN BOTH LI THAW AND LI FREEZE MODES
- DEVELOPED 2-D COMPUTER SIMULATION OF Li/NaK FREEZE/THAW WITH VIDEO GRAPHIC OUTPUT
- PERFORMED LONG TERM (3000 hr) HIGH TEMPERATURE Li/NaK CAPSULE TS TO VERIFY MIXTURE STABILITY
- FABRICATED OIL-WATER FLOW VISUALIZATION LOOP SIMULATOR



PNL ACCOMPLISHMENTS

- DESIGNED AND FABRICATED ULTRA-LIGHT HEAT PIPES WITH METAL FOIL LINERS AND HIGH STRENGTH WOVEN CERAMIC FIBER MANTLE
- TESTED FABRIC-FOIL HEAT PIPE WITH H₂O FLUID AND DELIVERED PROTOTYPE TO LeRC FOR MORE EXTENSIVE TESTING

JWS91 02 6-pm



EXPLORATION TECHNOLOGY

HIGH CAPACITY POWER

HEAT PIPE CODES

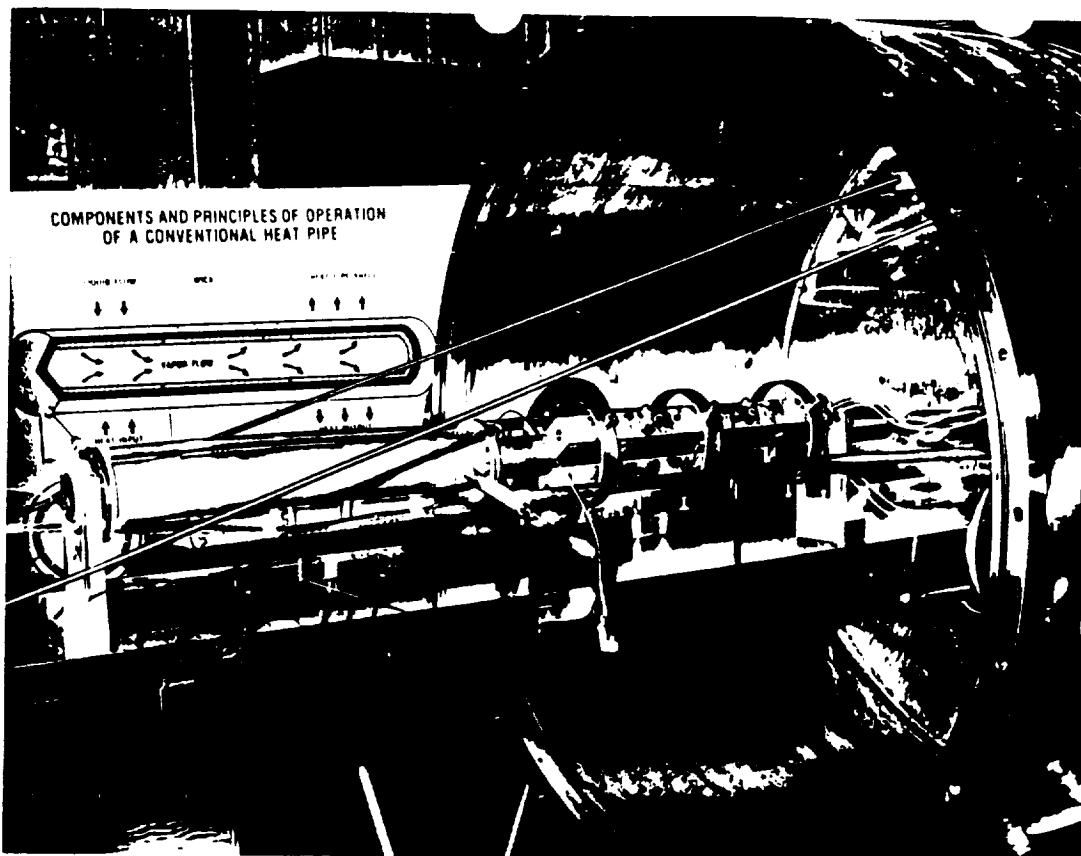
DEVELOPED STEADY STATE DESIGN CODE

- VALIDATED WITH SP-100 HEAT PIPE DATA
- INCORPORATED IN HEPSPARC RADIATOR DESIGN CODE
- IMPROVED VAPOR FLOW ALGORITHM
- WILL BE USED FOR HEAT PIPE DESIGN & AUDITS

TRANSIENT CODES

- JOINT EFFORT (NASA, AIR FORCE, WSU, UCLA, UNM)
- MODELS SP-100 HEAT PIPE START-UP FROM FROZEN STATE
- VAPOR FLOW REGIONS COMPLETED AND VALIDATED
- COMPLETED EXPERIMENTS FOR CODE VALIDATION

ITP RJWS91-001 18

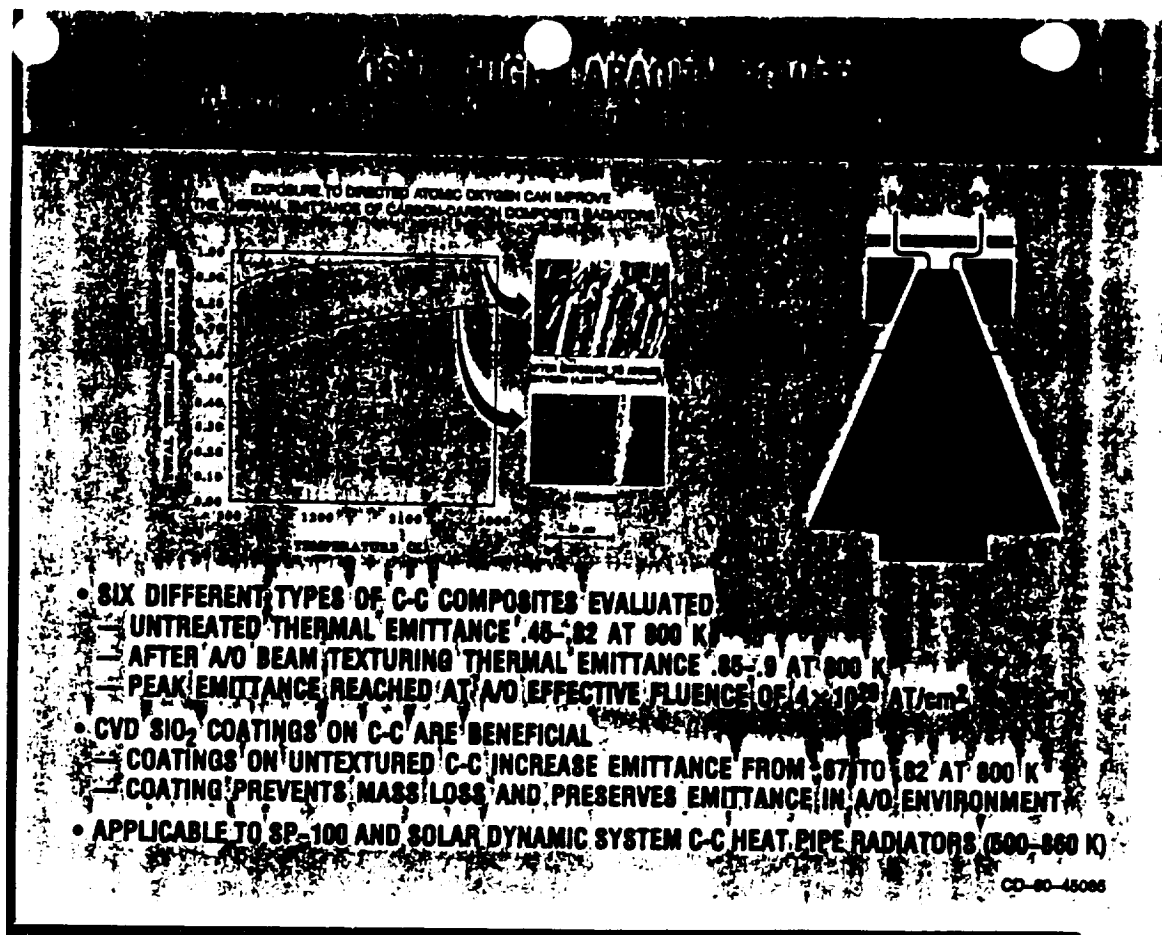
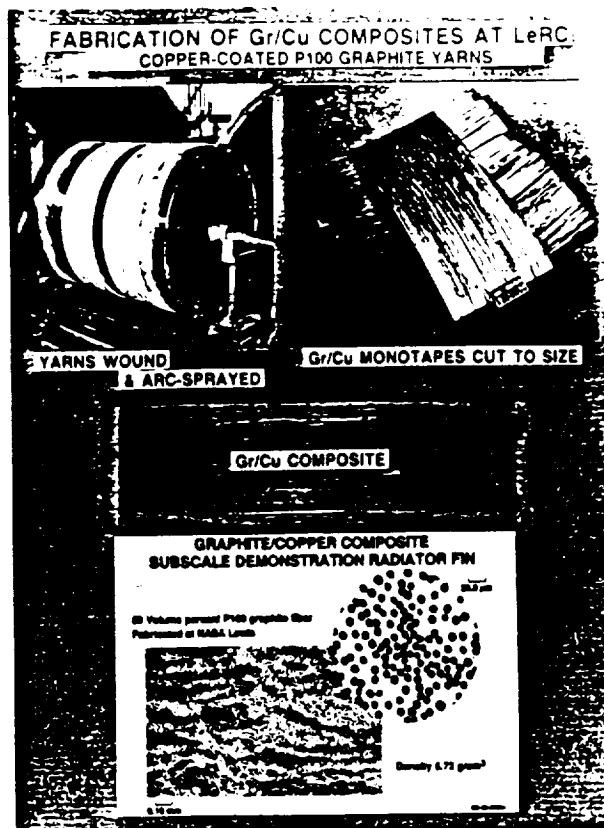


EXPLORATION TECHNOLOGY

HIGH CAPACITY POWER

NASA LeRC HEAT PIPE LABORATORY

- OPERATED WATER, LIQUID METAL HEAT PIPES
- FACILITY DATA ACQUISITION SYSTEM CHECK-OUT COMPLETE
- SIMULATE STIRLING AND THERMOELECTRIC RADIATOR OPERATING CONDITIONS
- INITIATING TESTS ON PNL FIBER-FABRIC HEAT PIPE
 - FUTURE TEST ON CONTRACTOR HEAT PIPES





ADVANCED MATERIALS

MAJOR OBJECTIVES:

**DEVELOP MATERIALS WITH SIGNIFICANTLY ENHANCED CHARACTERISTICS
COMPARED TO SOA RADIATOR AND REFRACTORY MATERIALS**

- RADIATOR FIN MATERIALS TO REPLACE Be WITH NO MASS PENALTY
- REFRACTORY MATERIAL/COMPOSITE WITH FACTORS 2 TO 10
IMPROVEMENT IN CREEP STRENGTH COMPARED TO Nb-1Zr
- DEVELOP DATA BASE TO QUALIFY ALL MATERIALS AT DESIGN
CONDITIONS (PWC-11, IN 718, IN 720, Cu/Gr, W/Nb, MoHfC/Nb)

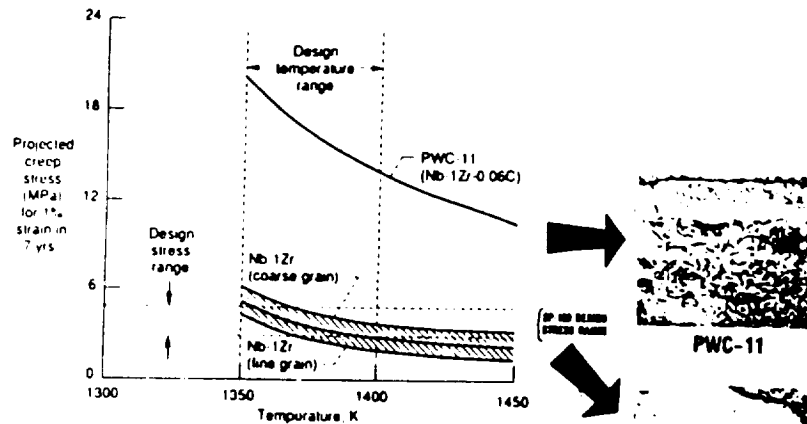
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**ADVANCED MATERIALS
MAJOR PROJECT ELEMENTS**

- **DEVELOPMENT OF PWC-11**
 - SPECIFICATION, FABRICATION, TESTING, APPLICATION (WELDING/JOINING)
- **DEVELOPMENT OF WIRE REINFORCED REFRACTORY COMPOSITES**
 - WIRE CHARACTERIZATION, COMPOSITE FABRICATION, TESTING, APPLICATIONS
- **MATERIAL SELECTION AND COMPATIBILITY DETERMINATION FOR SUPERALLOY
STIRLING DESIGNS AND REFRACTORY STIRLING DESIGNS**

PWC-11 Alternate for Nb-1Zr



PWC-11 PRECIPITATE CHARACTERIZATION

	AS-ROLLED	HEAT TREATED	TESTED
SIZE	1-10 μm	.85-10 μm	.18-.15 μm
STRUCTURE	bcp	lcc	lcc
COMPOSITION	Nb ₂ C	(Zr,Nb)C	(Zr,Nb)C

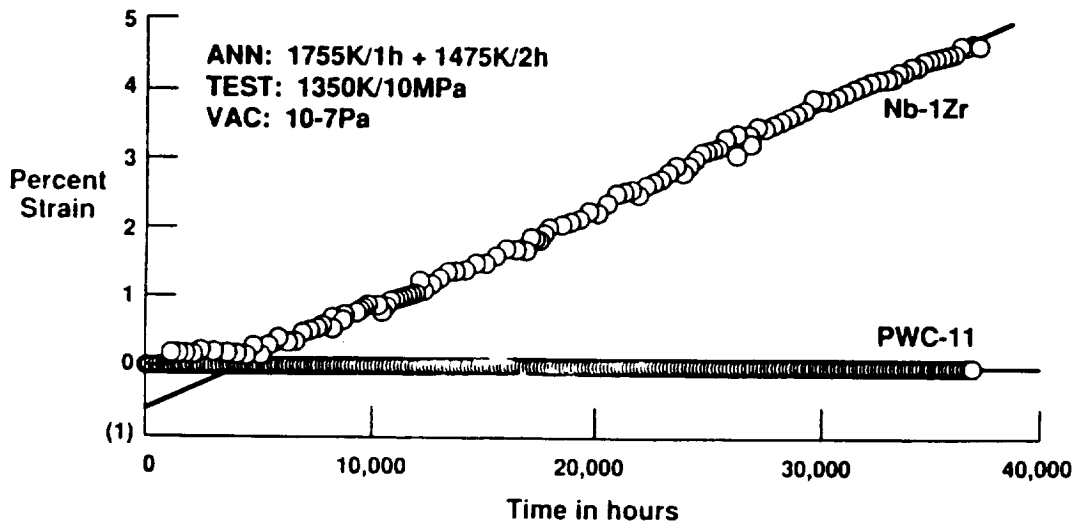
- Nb₂C TRANSFORMS TO STABLE (Zr,Nb)C PARTICLE
- AGING AT 1350-1400 K DOES NOT OVERGROW PRECIPITATE PARTICLE
- AFTER 35,000 h PRECIPITATE (Zr,Nb)C STILL EFFECTIVE STRENGTHENER



MATERIALS DIVISION

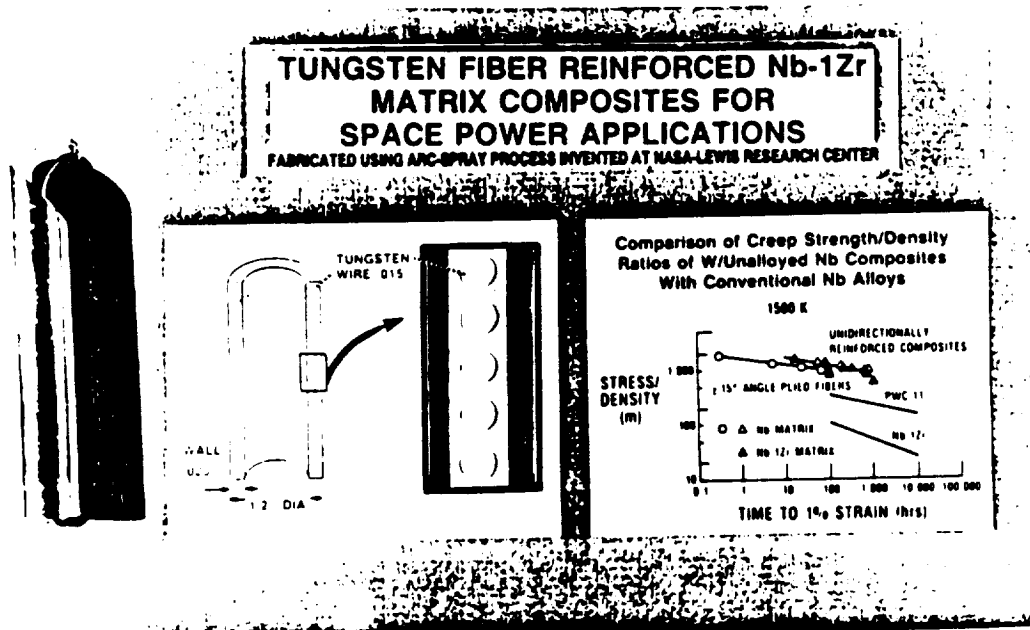
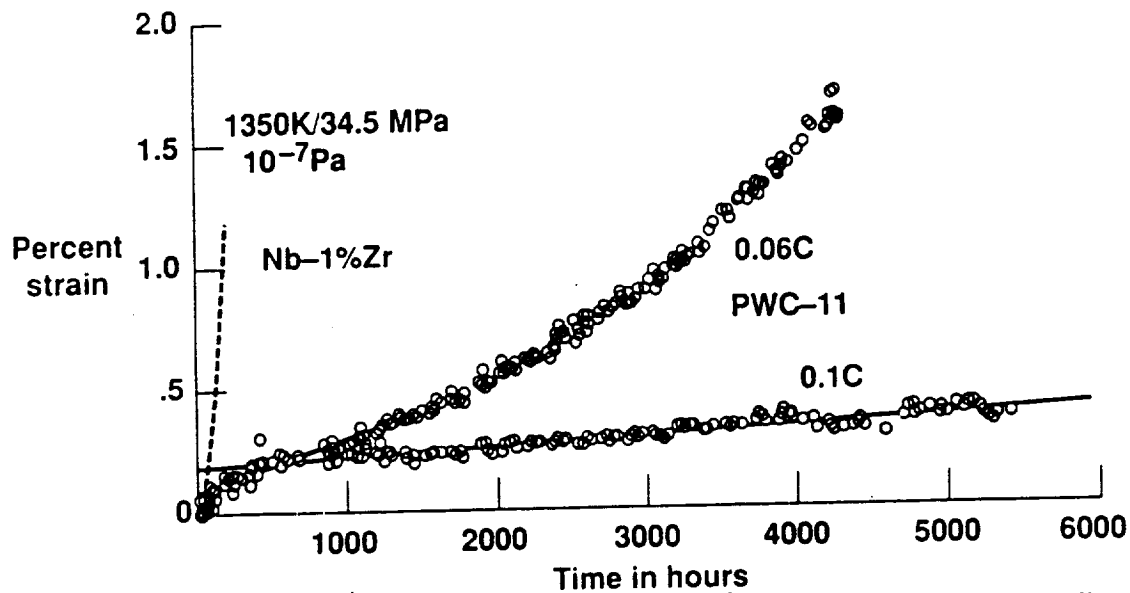


CREEP CURVES FOR Nb-1Zr & PWC-11 (0.06C)



CD-90-51223

Creep Curves for Nb-1% Zr and PWC-11





HIGH CAPACITY POWER REFRACTORY MATERIAL CANDIDATES FOR 1300K STIRLING

NASA

BASE MATERIAL	MP (K)	ρ (g/cc)	ALLOY NAME	COMPOSITION (wt%)	JOINABILITY	FABRICABILITY	ALLOY AVAILABILITY	DATA AVAILABILITY	VACUUM (torr)
W	3680	19.3	W-25Re-HfC	24-26% Re 1% HfC	5	4	4	3	10^{-6}
Ta	3270	16.6	ASTAR-811C	8% W 1% Re 1% HfC	8	8	10	5	10^{-8}
Mo	2880	10.2	TZM	0.08% Zr 0.5% Ti	2	8	10	4	10^{-6}
			TZC	1.25% Ti 0.1% Zr 0.15% C	2	6	10	4	10^{-6}
Mo/Re	2780	15.5	Mo-47.5 Re	47.5% Re bal Mo	8	6	8	3	10^{-6}
Nb	2740	8.6	FS-85	11% W 28% Ta 1% Zr	8	8	5	4	10^{-8}
			B-88	27% W 2% HfC	7	7	4	2	10^{-8}
			C-103	10% Hf 1% Ti 0.7% Zr	10	10	10	7	10^{-8}
			PWC-11	1% Zr 0.1% C	10	10	10	7	10^{-8}
			Nb-1Zr	1% Zr	10	10	10	8	10^{-8}

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HIGH CAPACITY POWER

NASA

POWER MANAGEMENT/SYSTEM DIAGNOSTICS

MAJOR OBJECTIVES:

DEVELOP PMAD ARCHITECTURE TO ENABLE USE OF FPSC's IN FUTURE MISSIONS

- CONTROL STABILITY, LOW MASS (1 kg/kWe), RELIABILITY (.99)

TEST POWER SWITCHES IN HIGH TEMPERATURE (425K), HIGH RADIATION (10^{13} n/cm, .5 Mrad gamma), ENVIRONMENTS

DEVELOP DIAGNOSTIC SENSORS AND SYSTEMS TO MONITOR NUCLEAR SYSTEM PERFORMANCE WITH EMI IMMUNITY AND SAFETY UNDER EXCESS CURRENT AND INSULATION BREAKDOWN CONDITIONS

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TECHNICAL HIGHLIGHTS

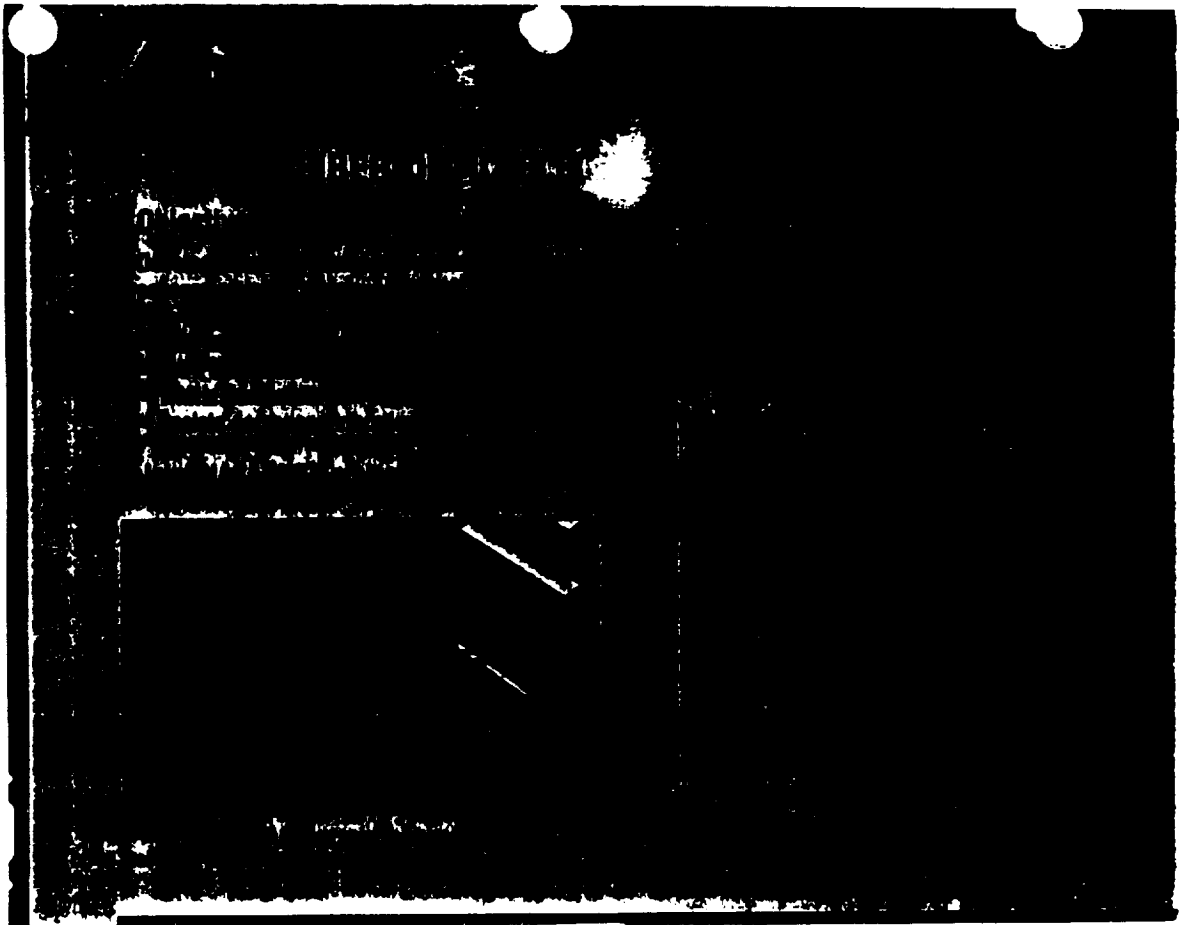
PMAD

- SET-UP TEST LABORATORY TO DEVELOP CONTROL TECHNIQUES FOR MULTIPLE FREE-PISTON STIRLING CONVERSION SYSTEMS
- QUALIFIED HIGH TEMPERATURE (525K) MAGNETIC MATERIALS FOR FPSE LINEAR ALTERNATOR - $\text{Sm}_2\text{Co}_{17}$
- IRRADIATED COMMERCIAL SEMI-CONDUCTOR POWER SWITCHES TO SP-100 SPECIFICATIONS - ALL DEGRADED
- BEGAN DEVELOPMENT OF SiC SWITCHES TO MEET REQUIREMENTS

SYSTEM DIAGNOSTICS

- FIBER OPTIC CURRENT SENSOR COMPLETE (IR&D 100 AWARD)
- FIBER OPTIC VOLTAGE SENSOR NEAR COMPLETION

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HIGH CAPACITY POWER



SPACE ENVIRONMENTAL EFFECTS

MAJOR OBJECTIVES:

**DEVELOP CODES AND EXPERIMENTAL CORRELATIONS TO PREDICT BEHAVIOR
OF HIGH POWER SYSTEMS UNDER RELEVANT ENVIRONMENTS**

- EPSAT CODE EXTENDED TO LUNAR AND MARS ENVIRONMENTS
(Atomic Oxygen, Meteoroids, Space Plasma, Ion Effluents)

ENSURE SAFETY AND LONG-LIFE OPERATION OF HIGH POWER SYSTEMS

ITP JMW91-001.7



HIGH CAPACITY POWER



TECHNICAL HIGHLIGHTS - ENVIRONMENTAL EFFECTS

- MEASURED ATOMIC OXYGEN IONIZED SPUTTERING YIELDS TO
CORRELATE WITH SP-100 MATERIALS AND DESIGNS
- MEASURED AND MODELED CURRENTS THROUGH CABLE
INSULATION PINHOLES
- MEASURED DIELECTRIC BREAKDOWN POTENTIAL BETWEEN
SPACE PLASMA AND SPACECRAFT

ITP JED91-001.5



HIGH CAPACITY POWER

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FULL-UP/AUGMENTED PROGRAMS

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HIGH CAPACITY POWER

NASA

BUDGETS, \$ M

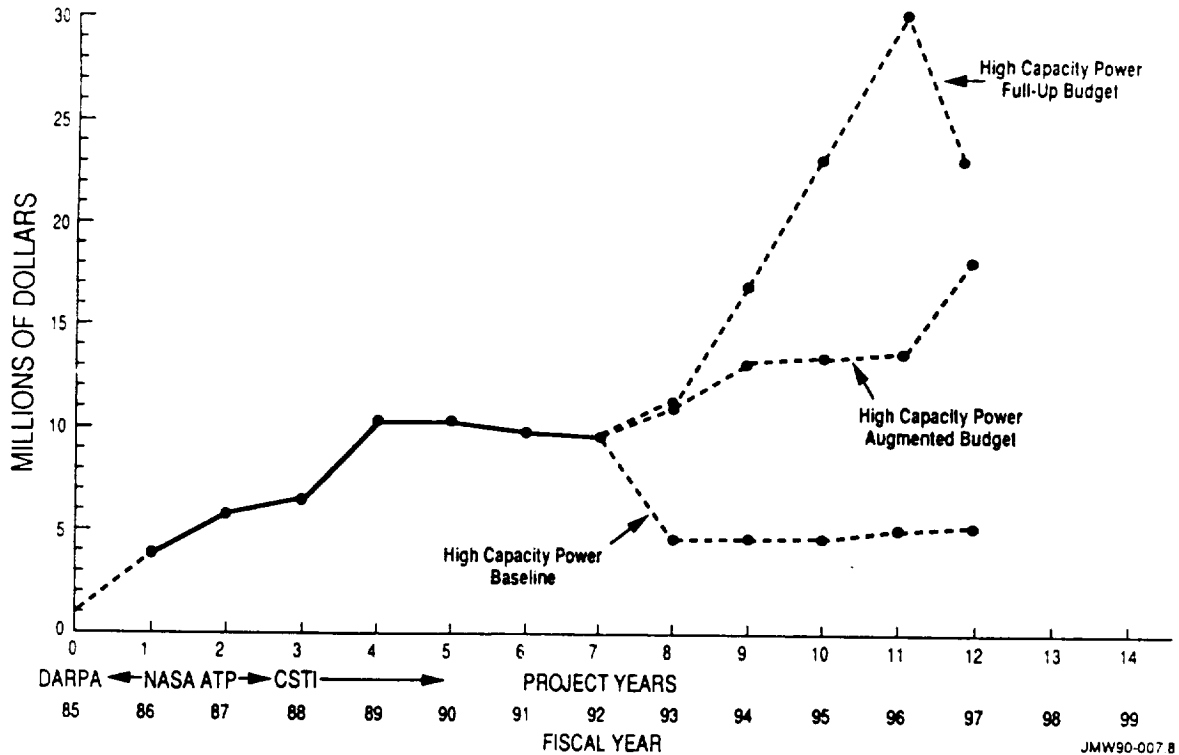
<u>YEAR</u>	<u>BASELINE</u>	<u>AUGMENTED</u>	<u>FULL-UP</u>
1991	10.4	10.4	10.4
1992	10.6	10.6	10.6
1993	4.5	10.9	11.1
1994	4.6	12.0	16.8
1995	4.8	12.3	23.0
1996	5.0	12.6	30.5
1997	5.2	18.0	23.0

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NASA

HIGH CAPACITY POWER GROSS FUNDING HISTORY/PROJECTIONS NASA SP-100 ATP - HIGH CAPACITY POWER



EXPLORATION TECHNOLOGY SURFACE SYSTEMS/OPERATIONS

OAET

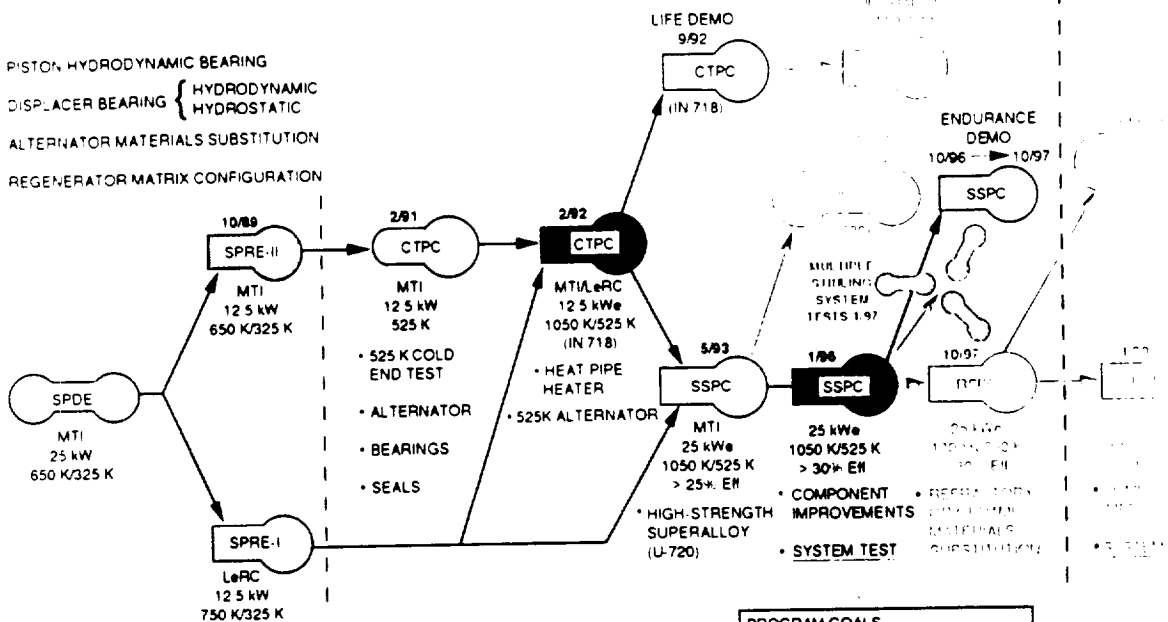
CURRENT PROGRAM

- 1050K SUPERALLOY STIRLING DEMONSTRATION- 25% EFF., 6 kg/kWe, 25 kWe - 1994
 - 30% IN 1996
 - 1 YEAR OPERATION IN 1997
- 450K WATER HEAT PIPE DEMONSTRATION < 5kg/m² - 1992
 - 525K RADIATOR SEGMENT DEMO IN 1994
- THERMOELECTRIC MATERIAL (SiGe/GaP) $Z = 1.0 \times 10^{-3} \text{ K}^{-1}$ DEMONSTRATED - 1994
- RADIATION HARD CIRCUITS DEVELOPED - 1995
- OPTIC POWER SENSING SYSTEM DEVELOPED - 1995
- ATOMIC OXYGEN, CO₂ ION, AND CO TESTING OF MATERIALS FOR MARTIAN SURFACE - 1997

ITP JMW91-001 B

STIRLING DEVELOPMENT FULL-UP BUDGET

- PISTON HYDRODYNAMIC BEARING
- DISPLACER BEARING { HYDRODYNAMIC
HYDROSTATIC
- ALTERNATOR MATERIALS SUBSTITUTION
- REGENERATOR MATRIX CONFIGURATION



- LOSS UNDERSTANDING AND REDUCTION
- CODE DEV AND VALIDATION
- DYNAMIC BALANCING
- LOSS SENSITIVITY AND PERFORMANCE IMPROVEMENTS

JMW91-006



EXPLORATION TECHNOLOGY

HIGH CAPACITY POWER

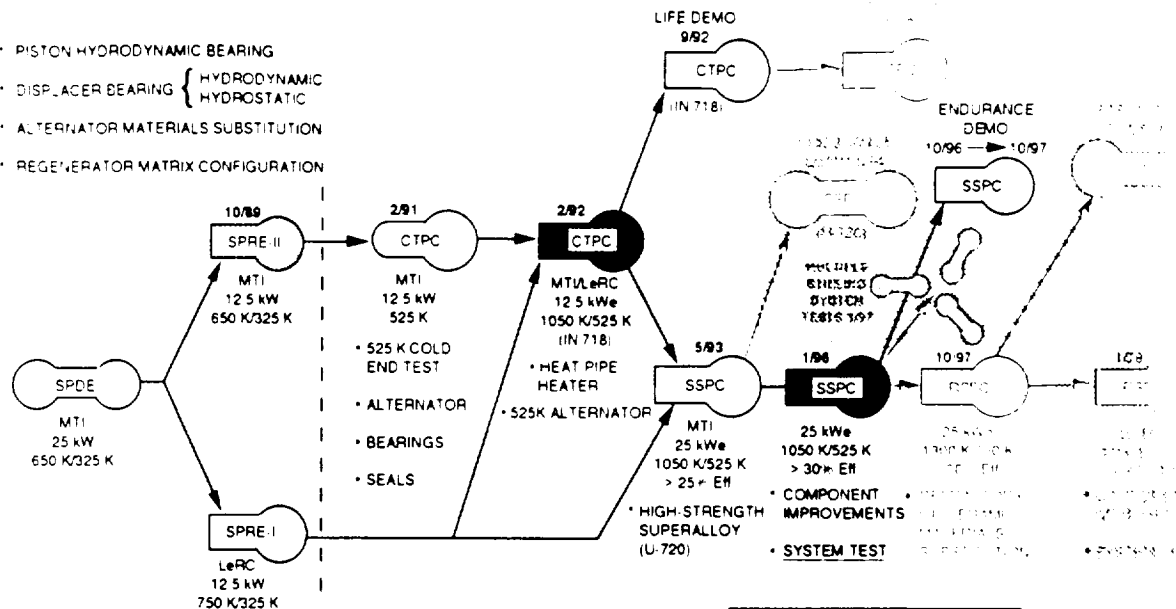
FULL-UP BUDGET PROGRAM

- FULL-UP PROGRAM CONTAINS ALL ELEMENTS AND CoF NECESSARY TO COMPLETE A 1300K FREE-PISTON STIRLING TEST IN 1997, PROVIDES SIGNIFICANT PROGRESS IN RADIATORS, MATERIALS, PMAD, ENVIRONMENTAL INTERACTIONS
 - 30% EFFICIENCY, 6 kg/kWe, 25 kW REFRACTORY POWER CONVERTER
 - MULTIPLE STIRLING SYSTEM TESTS FOR POWER SYSTEM PHASING AND CONTROL
 - 5 kg/m², 600K RADIATOR
 - FACILITIES TO PERFORM POWER CONVERSION/RADIATOR SYSTEM TESTS
 - ENDURANCE TESTS AND ACCELERATED LIFETIME MODELS/TECHNIQUES TO ASSURE 10 - 15 YEAR LIFE
 - 875K RADIATOR SEGMENT TESTS FOR THERMOELECTRICS
 - MATERIALS DATA BASE AND APPLICATION OF SUPERALLOYS, PWC-11, REFRACTORY COMPOSITES AND RADIATOR MATERIALS TO SYSTEM TESTS
- ALL OF THE DESIGNS, THE FACILITIES, AND MOST OF THE HARDWARE WILL BE IN PLACE AT THE END OF 1997 TO SUPPORT THE REFRACTORY STIRLING POWER CONVERTER SYSTEM TEST IN 1999 AND THE ENDURANCE TEST IN 2000

ITP RJ91-001.7

STIRLING DEVELOPMENT AUGMENTED BUDGET

- PISTON HYDRODYNAMIC BEARING
- DISPLACER BEARING { HYDRODYNAMIC
HYDROSTATIC
- ALTERNATOR MATERIALS SUBSTITUTION
- REGENERATOR MATRIX CONFIGURATION



- LOSS UNDERSTANDING AND REDUCTION
- CODE DEV. AND VALIDATION
- DYNAMIC BALANCING
- LOSS SENSITIVITY AND PERFORMANCE IMPROVEMENTS



EXPLORATION TECHNOLOGY

HIGH CAPACITY POWER

Δ AUGMENTED PROGRAM

ELIMINATES THE FOLLOWING:

- HARDWARE AND FACILITIES FOR 1300K STIRLING SYSTEM TEST
- DOUBLE-ENDED STIRLING ENDURANCE TESTS AT 1050K AND 1300K
- MULTIPLE STIRLING SYSTEM TEST
- BASIC UNDERSTANDING, CODE DEVELOPMENT AND CORRELATION TO REDUCE PROGRAM RISK
- THERMAL MANAGEMENT DEVELOPMENT FOR 1300K STIRLING SYSTEM TEST
- ADVANCED PMAD AND DIAGNOSTIC FULL SYSTEM DEVELOPMENT
- MODELLING DEVELOPMENT FOR LUNAR AND MARS ENVIRONMENTS, ION THRUSTER EFFLUENTS
- DETAILED MATERIAL DATA BASE AND APPLICATION DEVELOPMENT FOR ADVANCED ALLOYS AND COMPOSITES
- FACILITY DEVELOPMENT FOR REFRACTORY TESTING AT SIMULATED MARS CONDITIONS

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THERMAL MANAGEMENT BASELINE BUDGET

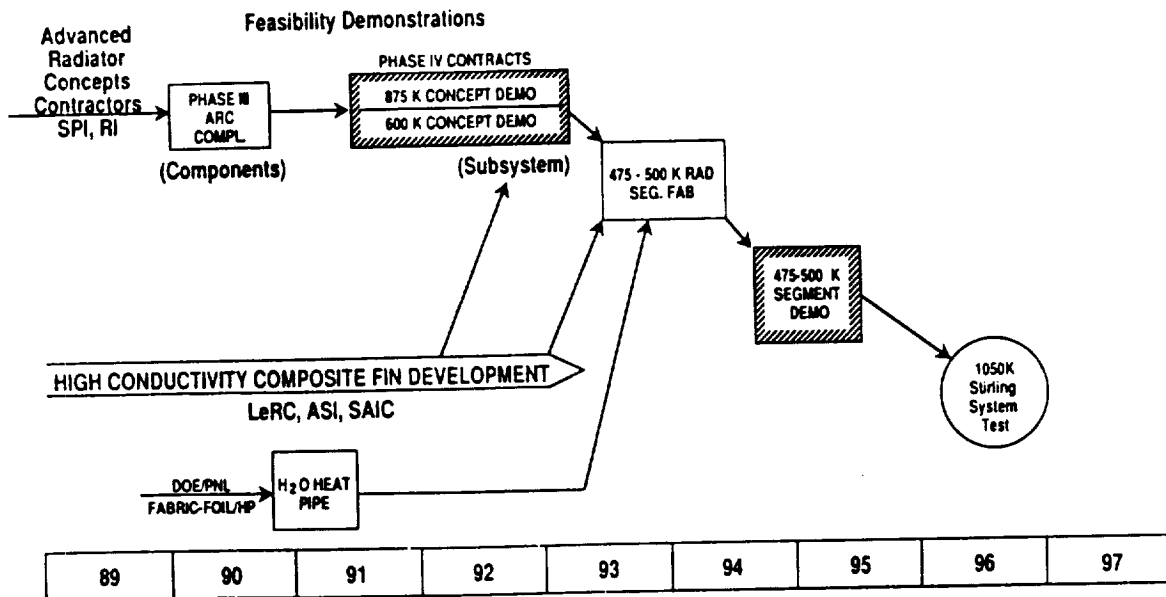
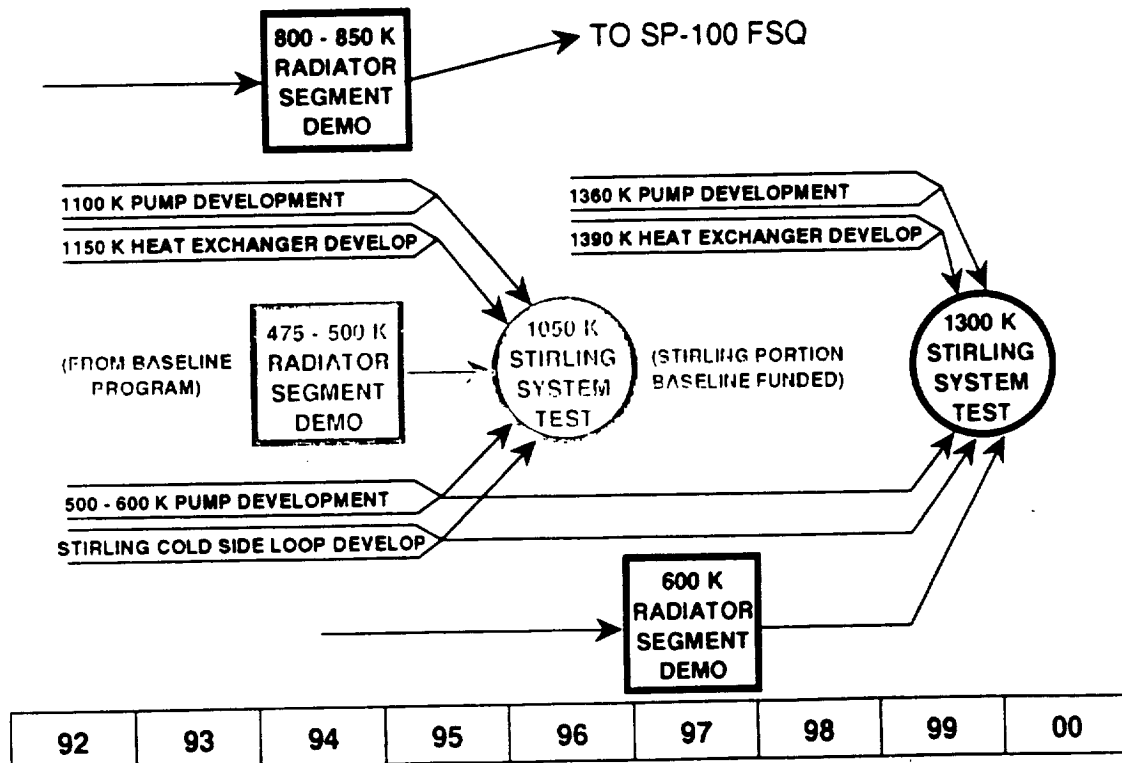


Figure 9

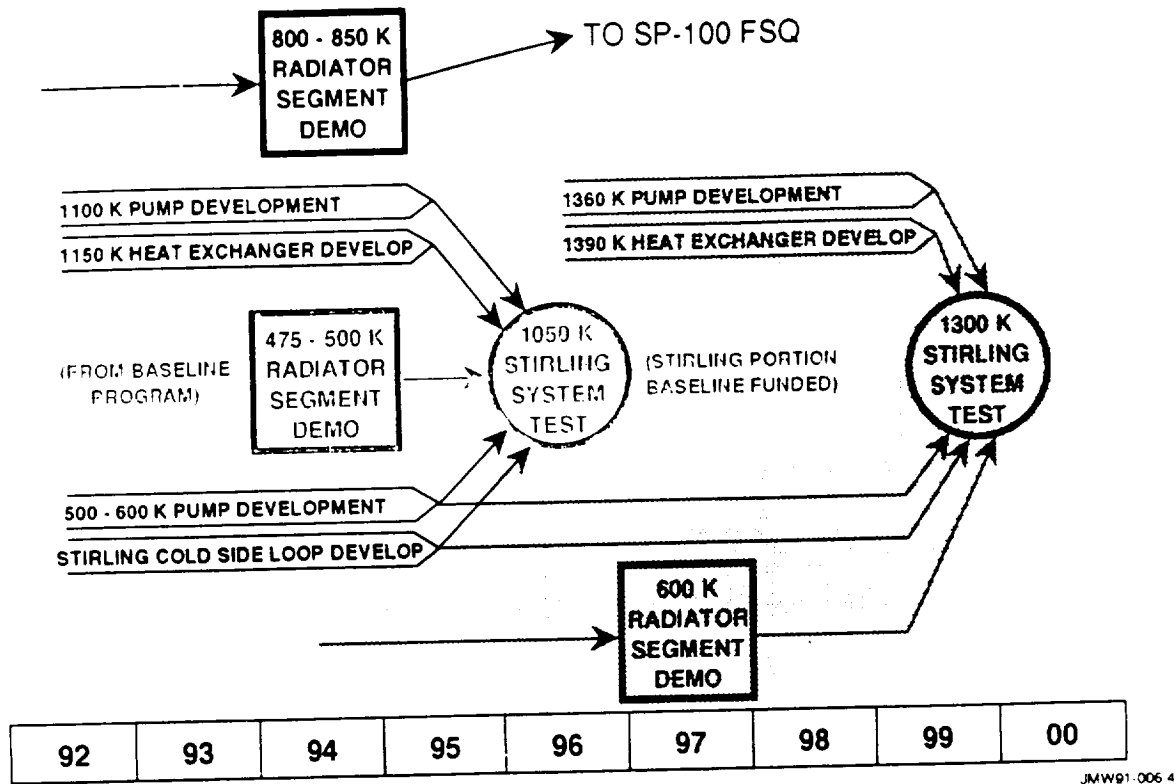
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THERMAL MANAGEMENT FULL-UP BUDGET



JMW91-006.2

THERMAL MANAGEMENT AUGMENTED BUDGET



EXPLORATION TECHNOLOGY =

HIGH CAPACITY POWER
PMAD/SYSTEM DIAGNOSTICS

FULL-UP BUDGET

- PMAD** • RADIATION-HARD CIRCUITS DEVELOPED AND DEMONSTRATED AT SYSTEM OPERATING CONDITIONS
- SOFT MAGNETIC MATERIALS COMPLETELY CHARACTERIZED FOR USE IN HIGH POWER, HIGH TEMPERATURE, SPACE POWER APPLICATIONS
 - COMPONENTS (TRANSFORMERS) DESIGNED AND TESTED IN RELEVANT ENVIRONMENTS

- DIAGNOSTICS** • DEVELOP EXTENDED RANGE OF OPERATION FOR POWER SENSORS (TEMPERATURE AND VIBRATION)
- SENSORS MODIFIED FOR PRODUCTION / THEN FLIGHT QUALIFIED

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HIGH CAPACITY POWER

PMAD/SYSTEM DIAGNOSTICS

AUGMENTED BUDGET

- PMAD • RADIATION-HARD DEVELOPMENTS RESTRICTED TO SWITCHES, NOT CIRCUITS
- LESS SOFT MAGNETIC MATERIALS CHARACTERIZED, NO COMPONENTS TESTED

- DIAGNOSTICS • RESTRICTED RANGE OF TEMPERATURE AND VIBRATION OPERATION
- MAY NOT FULLY QUALIFY FOR FLIGHT, NOT PRODUCTION ITEMS

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HIGH CAPACITY POWER



ENVIRONMENTAL INTERACTIONS

- BASELINE • ATOMIC OXYGEN, CO₂ ION, AND CO TESTING OF POWER SYSTEM MATERIALS FOR MARTIAN SURFACE APPLICATIONS

- AUGMENTATION • TESTING FOR PASCHEN BREAKDOWN OF HIGH VOLTAGE POWER SYSTEM GEOMETRIES IN LUNAR AND MARTIAN LOCAL ATMOSPHERIC CONDITIONS (AND DUST)

- FULL-UP • EPSAT - BASED MODELLING OF POWER SYSTEM INTERACTIONS WITH ION THRUSTER EFFLUENTS, ETC.
- MODEL/CORRELATION OF SYSTEM BEHAVIOR FOR LUNAR AND MARTIAN ENVIRONMENTS

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RELATED EFFORTS

- JPL BASE R&T EFFORT ON SILICIDE THERMOELECTRICS WITH POTENTIAL ORDER OF MAGNITUDE IMPROVEMENT IN Z
- DOE SOLAR STIRLING DEVELOPMENT - 1050K, 25 kWe/CYLINDER
- GE SP-100 CONTRACT FOR THERMOELECTRIC MODULES (Z = .85) AND SPACE RADIATORS
- DOD DEVELOPMENT OF SURVIVABLE SPACE RADIATOR TECHNOLOGY
 - CODE DEVELOPMENT
- DOD DEVELOPMENT OF RADIATION HARD SENSOR TECHNOLOGY
- DOD DEVELOPMENT OF EARTH ORBITAL ENVIRONMENTAL INTERACTIONS MODELS/EXPERIMENTS - EPSAT

ITP RJS91-001.9

FOCUSED TECHNOLOGY: HIGH CAPACITY POWER SUMMARY

OAET

- **IMPACT:**
 - Advanced conversion (Stirling/Thermoelectric) coupled to an SP-100 reactor will provide the enabling technology for the development of lunar and Mars surface power systems
- **USER COORDINATION:**
 - SEI technology requirement for Surface Systems and NEP being developed co-operatively with RP, RZ, JSC PSS - - High Priority in RZ
 - Planetary science requirements being developed with OSSA and with JPL
- **OVERALL TECHNICAL AND PROGRAMMATIC STATUS:**
 - Significant progress in all areas including Conversion Systems, Thermal Management, PMAD, Space Environment, and Materials Development
 - Stirling cold end component test successful at 525 K
 - Some program elements have been delayed by complex component fabrication issues and subscale feasibility test delays - - major out-year milestones not yet delayed
- **MAJOR TECHNICAL/PROGRAMMATIC ISSUES**
 - Lack of clear user commitment has delayed nuclear heat source development
 - Development/qualification of seven-year lifetime systems and technology to facilitate fifteen to twenty year overall lifetime

JMW91-005.4



HIGH CAPACITY POWER

CONCLUDING REMARKS

- HIGH CAPACITY POWER
 - BROAD-BASED PROGRAM
 - KEY ELEMENTS
 - SIGNIFICANT PROGRESS TO DATE
- CURRENT PROGRAM MEETS MANY KEY MILESTONES
- STRATEGIC PROGRAM NECESSARY TO BRING ALL PROGRAM ELEMENTS TO FRUITION
- AUGMENTED PROGRAM PROVIDES EARLY 1050K STIRLING ENDURANCE TEST, PLUS DESIGN, FAB, AND TEST OF A 1300K REFRACTORY STIRLING AND SELECTED CRITICAL SUBSYSTEMS

ITP.FJS91-001.11



SURFACE POWER AND THERMAL MANAGEMENT

BY

JOHN M. BOZEK
NASA LEWIS RESEARCH CENTER

ITP EXTERNAL REVIEW

JUNE 27, 1991

ITP JMB91-002.1



Surface Power and Thermal Management

OBJECTIVES

- **Programmatic**
Develop Solar-Based Power and Low-Grade Heat Thermal Management Technologies to Support Lunar and Mars Surface System Operations
- **Technical**
 - Power System - 25 kWe @ 3 We/kg (Lunar), 8 We/kg (Mars)
 - Fuel Cell Life - 20,000 hrs operational life
 - RFC Energy Density - 500 to 1000 W-hr/kg
 - Thermal Ops. - 60K to 400K with Long Life
 - Photovoltaics - ≥ 300 W/kg (AMO)
 - Electrical - ≤ 55 kg/kWe

SCHEDULE

- 1993 Select RFC PEM Membrane(s)
- 1994 Complete Thermal Model for RFC
- 1995 Full Area Fuel Cell
PV Cell Choice
50% Improvement in Cryo Heat Pipes
- 1996 300% Heat Pump Improvement
Stable Electrical Transmission
Fuel Cell Stacks Fabricated
- 1997 5,000 hrs on Fuel Cell Stack w/SOA Electrolyzer
PV Cell/Blk/Structure Integrated
- 1998 1 yr Life Test on EPM Bread-Board
Ground Verification of RFC/TPM
TPM Flight Experiment Design
- 1999 Complete RFC B-B Test (Adv. FL/EL/Tanks)
- 2000 Bread-Board Performance of TD&C
3 W/kg, 20,000 hr Lunar Power System Reference Design

RESOURCES

	CURRENT	"3X"	STRATEGIC
• 1991	\$ 0.6 M	\$ 0.6 M	\$ 0.6 M
• 1992	\$ 0 M	\$ 0 M	\$ 0 M
• 1993	\$ 0 M	\$ 3.4 M	\$ 5.0 M
• 1994	\$ 0 M	\$ 9.0 M	\$ 11.7 M
• 1995	\$ 0 M	\$ 12.6 M	\$ 18.5 M
• 1996	\$ 0 M	\$ 14.0 M	\$ 24.2 M
• 1997	\$ 0 M	\$ 18.0 M	\$ 25.3 M
• BTC	\$ 0 M	\$ 9.0 M	\$ 35.0 M

POTENTIAL PARTICIPANTS

- **Lewis Research Center**
Lead; Analysis, Energy Storage, EPM, Thermal Mgt., PV
- **Jet Propulsion Laboratory**
Supporting PV Arrays, Energy Storage, Analysis, Thermal Mgt.
- **Johnson Space Center**
Supporting Energy Storage & Thermal Mgt.
- **Goddard Space Flight Center**
Supporting Low-Temperature Thermal Mgt.
- **Los Alamos National Laboratory**
Supporting Energy Storage Component Testing

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EXPLORATION TECHNOLOGY=

SURFACE POWER AND THERMAL MANAGEMENT

WHAT IS IT ?

FOCUSED TECHNOLOGY PROJECT (ELEMENT OF EXPLORATION TECHNOLOGY PROGRAM)

FOCUSED ON EXTRATERRESTRIAL SURFACES (LUNAR & MARS)

FOCUSED ON SOLAR-BASED POWER (REGENERATIVE)

FOCUSED ON ENERGY STORAGE (REGENERATIVE FUEL CELLS)

FOCUSED ON POWER GENERATION (PHOTOVOLTAICS)

FOCUSED ON ELECTRICAL POWER MANAGEMENT (TEMP. & POWER)

FOCUSED ON THERMAL POWER MANAGEMENT (3 R'S)

FOCUSED HARDWARE THAT IS SCALABLE TO NEEDS (TEST BEDS)

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EXPLORATION TECHNOLOGY=

SURFACE POWER AND THERMAL MANAGEMENT

PROJECT SUPPORTS EXPLORATION PROGRAM

THRU

FOCUSED TECHNOLOGY VERIFICATION

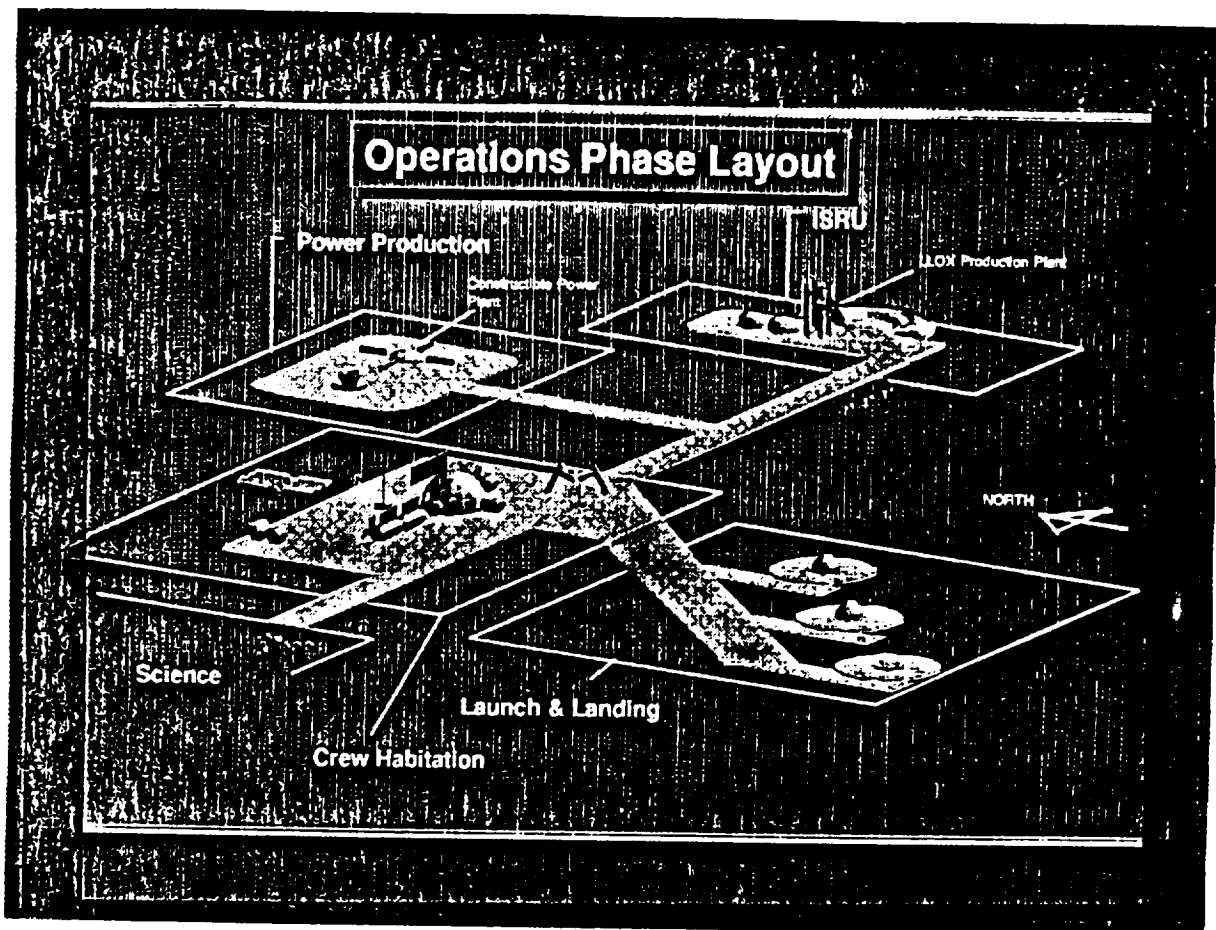
OF

ALL SOLAR-BASED POWER SYSTEM TECHNOLOGIES

AND

LOW-GRADE THERMAL MANAGEMENT TECHNOLOGIES

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=====EXPLORATION TECHNOLOGY=====

SURFACE POWER AND THERMAL MANAGEMENT

OBJECTIVE

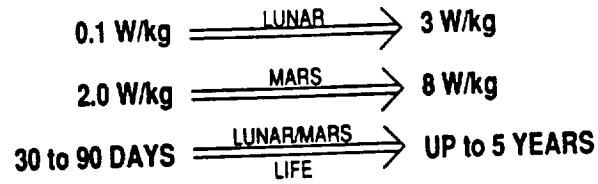
DEVELOP SOLAR-BASED POWER AND THERMAL
MANAGEMENT TECHNOLOGY TO A LEVEL OF
 READINESS SUFFICIENT TO ENABLE OR ENHANCE
 EXTRATERRESTRIAL SURFACE MISSIONS IN THE
 21st CENTURY



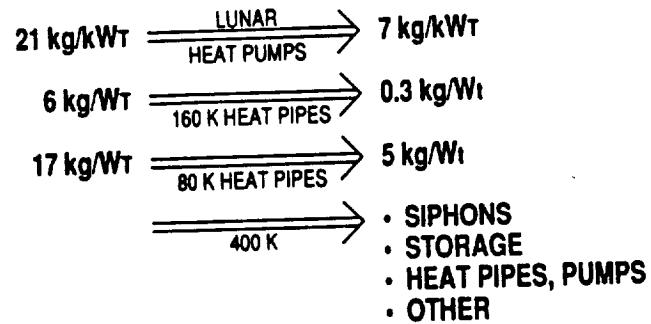
SURFACE POWER AND THERMAL MANAGEMENT

GOALS

POWER SYSTEM



THERMAL MANAGEMENT



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SURFACE POWER AND THERMAL MANAGEMENT

TECHNOLOGY CHALLENGE

- COMPATIBLE TECHNOLOGIES FOR INTEGRATED SYSTEM
- LONG LIFE RFC WITHOUT SACRIFICING PERFORMANCE
- HIGH POWER DENSITY, ROBUST PHOTOVOLTAICS
- LOW MASS, RELIABLE, ENVIRONMENTALLY COMPATIBLE ELECTRICAL SUBSYSTEM
- LOW MASS, LONG LIFE, HIGH PERFORMANCE THERMAL REJECTION, RETENTION, AND REDISTRIBUTION

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SURFACE POWER AND THERMAL MANAGEMENT

STRATEGIC PROGRAM ELEMENT

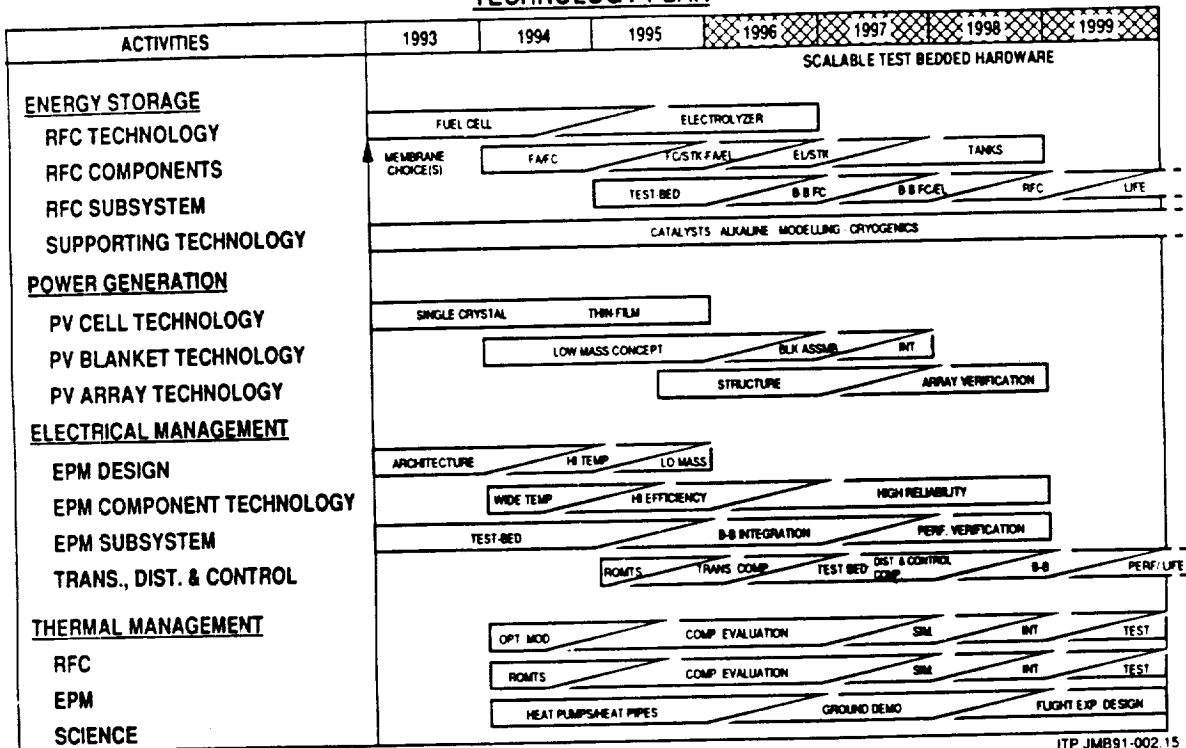
- SYSTEM INTEGRATION
 - TRADE STUDIES: INNOVATIVE TECHNOLOGY FEASIBILITY
 - REFERENCE DESIGNS [3 W/kg (Lunar); 8 W/kg (Mars)]
- ENERGY STORAGE (RFC's)
 - FUEL CELLS [Life/Efficiency]
 - ELECTROLYZERS [Life/Efficiency]
 - REACTANT STORAGE [Life/Mass/Volume]
 - TEST BEDDED SUBSYSTEM [Life/Performance]
- POWER GENERATION (PV's)
 - CELLS [Life/Efficiency]
 - BLANKET [Mass]
 - STRUCTURE [Deployment]
 - SCALABLE ARRAY PERFORMANCE [AMO/Vacuum/Thermal]
- ELECTRICAL MANAGEMENT
 - INTEGRATION OF POWER SUBSYSTEMS [Mass, Temp., Efficiency, Reliability]
 - TRANSMISSION, DISTRIBUTION AND CONTROL [Mass, Temp., Autonomy, Environment]
 - TEST BEDDED SUBSYSTEM
- THERMAL MANAGEMENT
 - MODELING [Requirements]
 - COMPONENTS [Rejection, Retention, Redistribution]
 - TEST BEDDED SUBSYSTEM [RFC, EPM/TD&C, Science]
 - FLIGHT EXPERIMENT WHERE NECESSARY

ITP JMB91-002.13



SURFACE POWER AND THERMAL MANAGEMENT

TECHNOLOGY PLAN



ITP JMB91-002.15



SURFACE POWER AND THERMAL MANAGEMENT

SUMMARY

IMPACT:

- PROVIDES FOR EARLY DEPLOYMENT OF NEEDED POWER FOR LUNAR BASE
- MEETS MASS, VOLUME AND OPERATIONAL CONSTRAINTS
- SYNERGISTIC WITH MARS MISSION

USER COORDINATION:

- CODE RZ: OAET/SPACE EXPLORATION: PSS/JSC
- CODE M: OFFICE OF SPACE FLIGHT (OSF)
- CODE S: OFFICE OF SPACE SCIENCE AND APPLICATION (OSSA)

OVERALL TECHNICAL AND PROGRAMMATIC STATUS:

- CRITICAL SYSTEM ELEMENTS IDENTIFIED
- PEM FUEL CELL LIFE (>1000 HOURS)
- RETRENCH TO BASE R&T IN FY92
- SYNERGISTIC PROGRAMS ADVANCING TECHNOLOGY OUTSIDE AGENCY

MAJOR TECHNICAL/PROGRAMMATIC ISSUES:

- REQUIREMENTS EVOLVING
- NUCLEAR (REACTOR/DIPS) AVAILABILITY

ITP JMB91-002.16



TECHNOLOGY BACK-UP

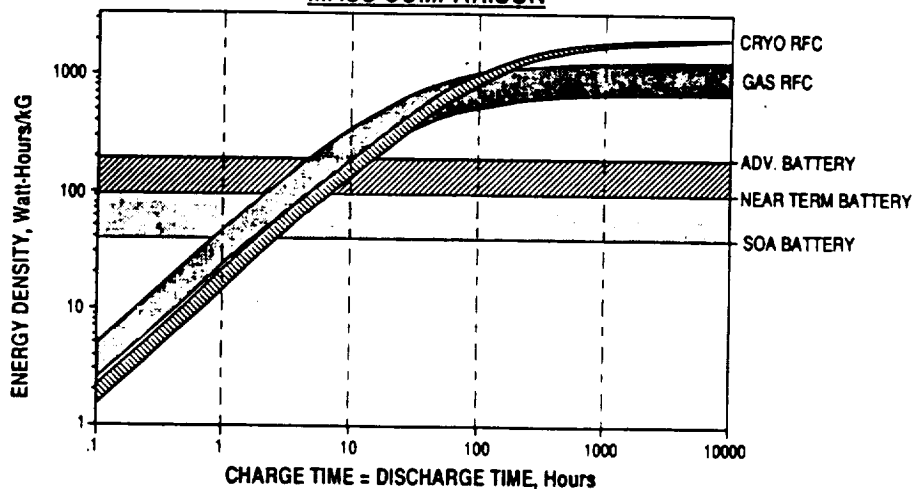
ITP-JMB91-002 19



SURFACE POWER AND THERMAL MANAGEMENT

REGENERATIVE FUEL CELL vs BATTERIES

MASS COMPARISON



DISCHARGE = CHARGE TIME

- < 1 HOUR
- > 1 HOUR but < 10 HOURS
- > 10 HOURS but < 100 HOURS
- > 100 HOURS

TECHNOLOGY OF CHOICE *

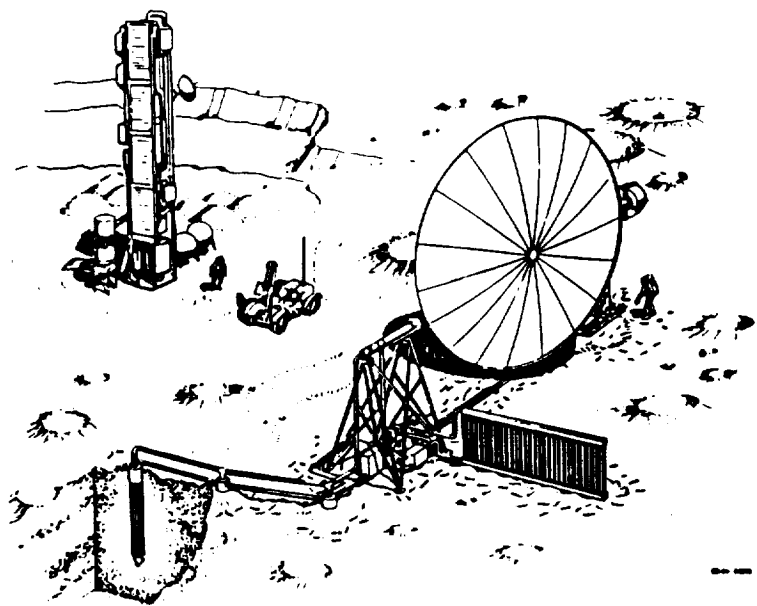
- BATTERIES
- BATTERIES or GAS RFC
- GAS RFC or CRYO RFC
- CRYO RFC

* CHOICE BASED ON MASS OF ENERGY STORAGE SYSTEM ONLY

ITP-JMB91-002 9



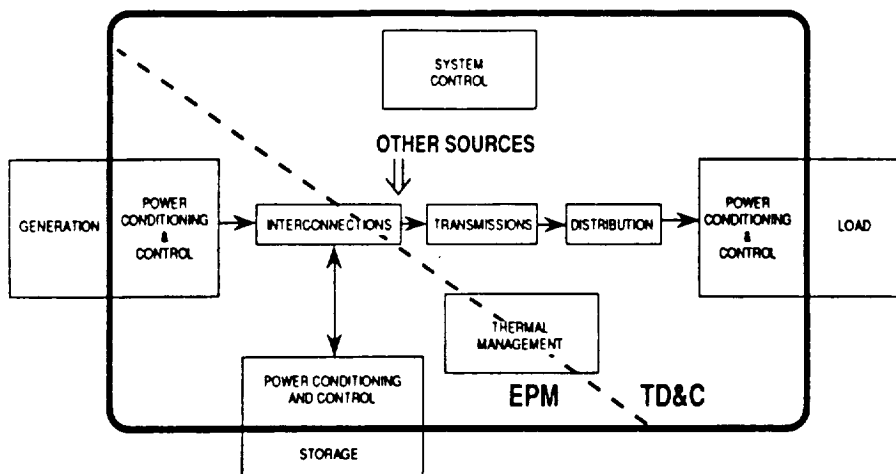
SURFACE POWER AND THERMAL MANAGEMENT





SURFACE POWER AND THERMAL MANAGEMENT

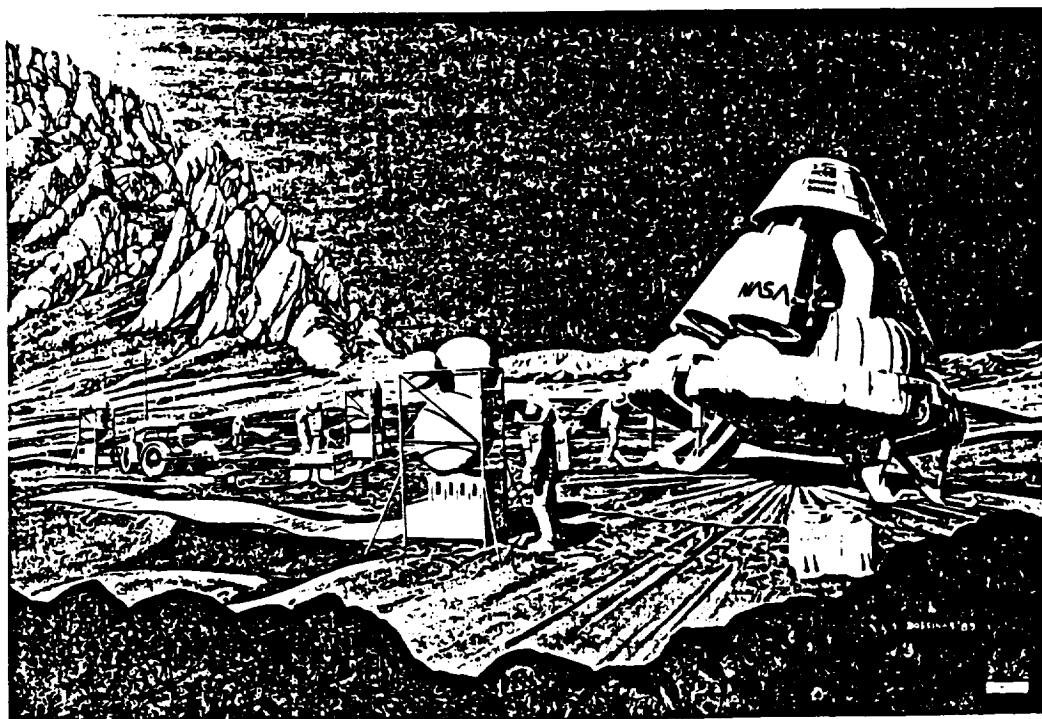
PMAD ELEMENTS (EPM and TD&C)

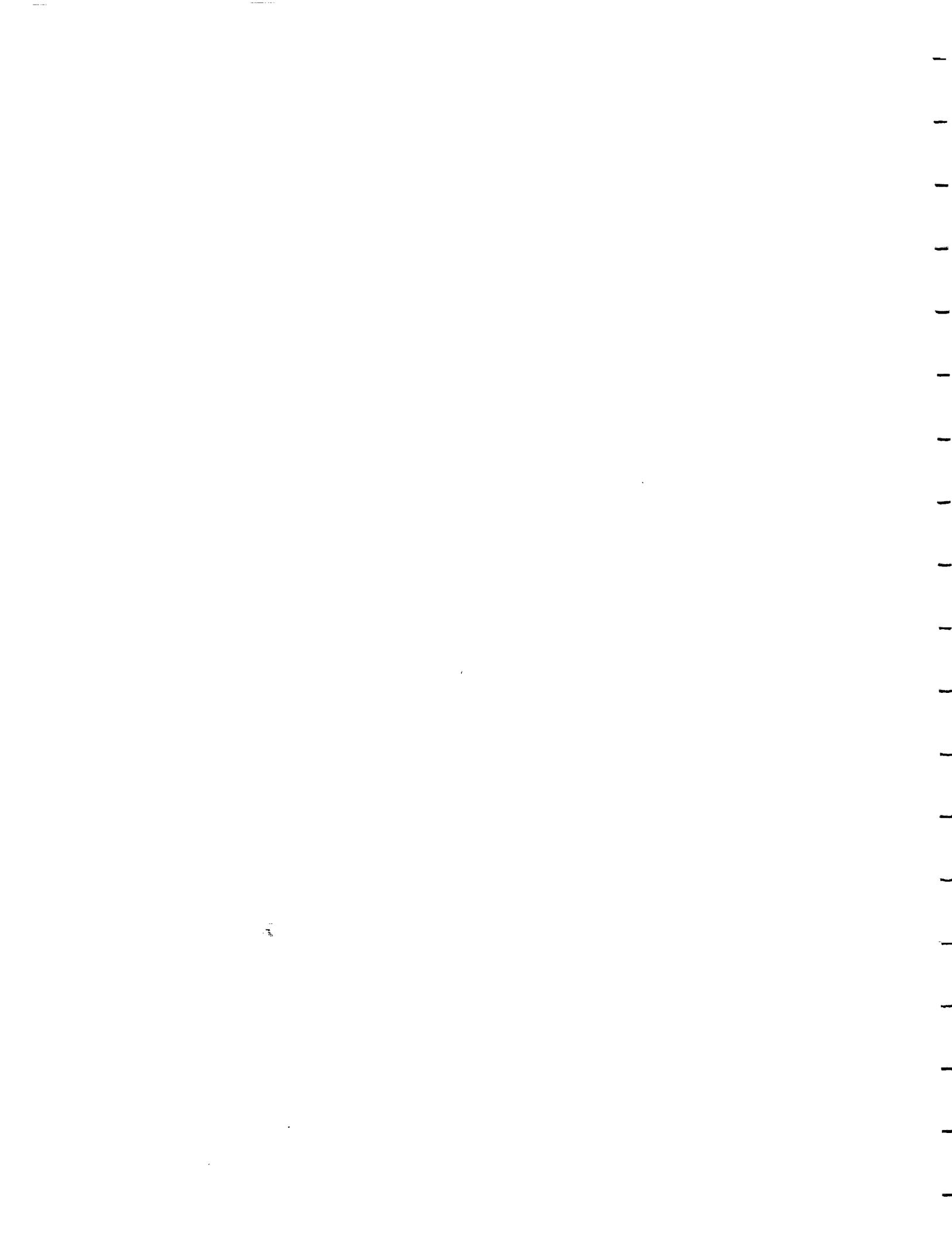


EPM : 110 kg/kW → 55 kg/kW

TD&C : MISSION DEPENDENT

ITP-JMB91-002.10





SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS

(INCLUDES SPACE STATIONS)

OAET

POWER AND THERMAL MANAGEMENT

**SPACE PLATFORMS FOCUSED TECHNOLOGY PROGRAM
POWER AND THERMAL MANAGEMENT**

PRESENTATION TO:

THE ITP EXTERNAL EXPERT REVIEW TEAM

RONALD C. CULL

JUNE 27, 1991

SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS

(INCLUDES SPACE STATIONS)

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POWER AND THERMAL MANAGEMENT

AGENDA

THE PROBLEM

HOW ADDRESSED

MARKET SURVEY

WHAT'S NEEDED

WHAT IMPACT

HOW DO WE GET THERE

SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS

(INCLUDES SPACE STATIONS)

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POWER AND THERMAL MANAGEMENT

THE PROBLEM

- ENERGY IS CRUCIAL FOR ALL ACTIVITIES IN SPACE
 - ELECTRICAL POWER
 - THERMAL MANAGEMENT
- EXTREMELY COSTLY
 - \$600 - 800/kW hr.
- NEW MISSIONS REQUIRE CONSIDERABLY MORE
 - SSF
 - EOS
 - ADTRSS

RC ITP91 01-16 pm

SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS

(INCLUDES SPACE STATIONS)

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POWER AND THERMAL MANAGEMENT

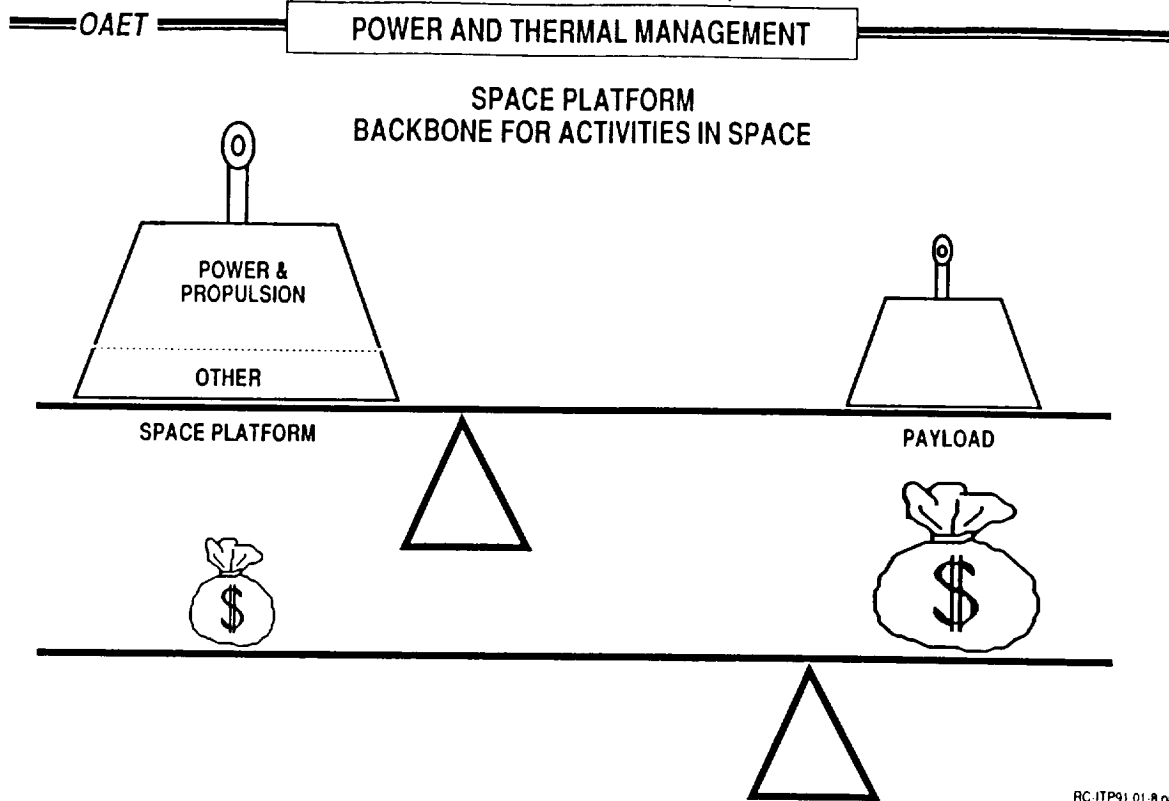
POSSIBLE SOLUTIONS

- CUT BACK MISSION RETURNS
 - TIME AVAILABLE
 - QUANTITY
 - QUALITY
 - LIFETIME
- MAKE USER MORE EFFICIENT
 - HIGHER EFFICIENCY LOADS
 - LOAD SCHEDULING AND MANAGEMENT
- IMPROVE TECHNOLOGY
 - MASS
 - EFFICIENCY
 - COST

RC ITP91 01-17 pm

SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS
(INCLUDES SPACE STATIONS)

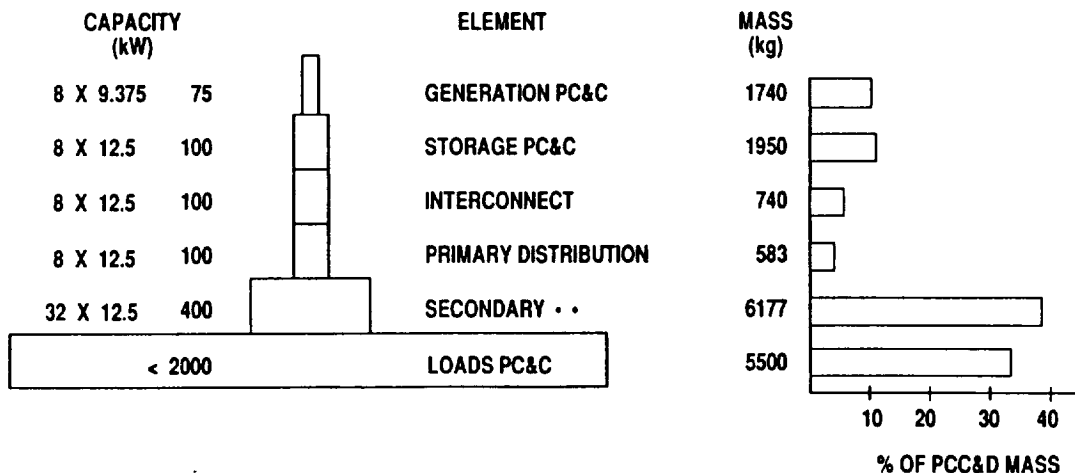


SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS
(INCLUDES SPACE STATIONS)



LOAD MANAGEMENT IMPACT (SSF EXAMPLE)



SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS

(INCLUDES SPACE STATIONS)

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POWER AND THERMAL MANAGEMENT

PHILOSOPHY

- **SCOPE OF NEAR EARTH SPACE ACTIVITIES DETERMINED BY FEDERAL BUDGET REALITIES**
- **TECHNOLOGY CAN BROADEN SCOPE WITHIN CONSTANT BUDGET**
 - NUMBER OF MISSIONS
 - LIFE OF MISSIONS
 - QUALITY OF MISSIONS
- **PLATFORM TECHNOLOGY THRUSTS SHOULD FOCUS ON BROADENING SCOPE**
 - TOWARD LONG LIFE
 - TOWARD IMPROVED PERFORMANCE
 - TOWARD LOW COST

RC-ITP91 01-3 pm

SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS

(INCLUDES SPACE STATIONS)

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POWER AND THERMAL MANAGEMENT

PHILOSOPHY

(CONT.)

- **MANY TECHNOLOGIES CURRENTLY UNDER DEVELOPMENT**
 - LEVEL OF EFFORT INADEQUATE FOR TIMELY DEVELOPMENT
 - UNFOCUSED
- **SPACE PLATFORM TECHNOLOGY PROGRAM SHOULD FOCUS ON THOSE TECHNOLOGIES THAT:**
 - MAKE SIGNIFICANT IMPACT
 - BROADLY APPLICABLE
 - CAN BE READY IN TIME

RC-ITP91 01-4 pm

SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS

(INCLUDES SPACE STATIONS)

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POWER AND THERMAL MANAGEMENT

PROGRAM FORMULATION

- IDENTIFY MARKET (USERS)
- DEFINE POWER AND THERMAL REQUIREMENTS
 - MISSION DOMAINS
 - MISSION UNIQUE
- ASSESS TECHNOLOGY IMPACT
- IDENTIFY CRITICAL TECHNOLOGY
- OUTLINE TECHNOLOGY DEVELOPMENT PLANS
 - INTEGRATED OBJECTIVES
 - ROADMAPS
 - FUNDING REQUIREMENTS
 - MILESTONES & DELIVERABLES

RC ITP91 01 5 pm

SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS

(INCLUDES SPACE STATIONS)

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POWER AND THERMAL MANAGEMENT

MARKET

- APPLICATIONS
 - EARTH OBSERVING (EOS)
 - ADVANCED COMMUNICATIONS (ATDRSS)
 - ADVANCED SPACE STATIONS (SSF)
- MISSIONS
 - MANNED/UNMANNED
 - CIVIL/COMMERCIAL
- ORBIT REQUIREMENTS
 - LEO → GEO
 - EQUATORIAL → POLAR
- POWER LEVELS
 - 10's W → 10's kW

SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS

(INCLUDES SPACE STATIONS)

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POWER AND THERMAL MANAGEMENT

SYSTEM REQUIREMENTS

- NEED TO SIGNIFICANTLY IMPROVE NEW SYSTEM DRIVERS
 - LIFE
 - RELIABILITY
 - MAINTAINABILITY
 - ADAPTABILITY
- WHILE MAINTAINING/IMPROVING TRADITIONAL DRIVERS
 - MASS
 - EFFICIENCY
 - COST
- BY IMPROVING TECHNOLOGY
- BY ADDING ATTRIBUTES
 - RECONFIGURABLE
 - SERVICEABLE
 - FAULT TOLERANT
 - AUTONOMOUS

RC-ITP91 01-6 pm

SPACE PLATFORMS TECHNOLOGY PROGRAM

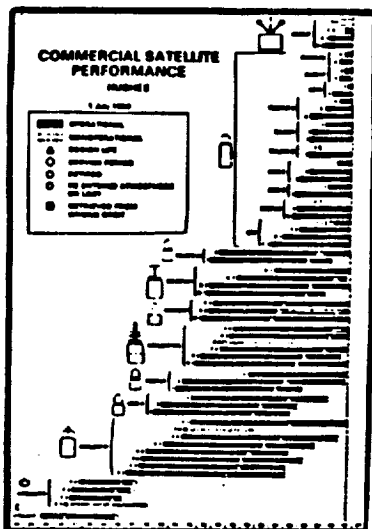
EARTH ORBITING PLATFORMS

(INCLUDES SPACE STATIONS)

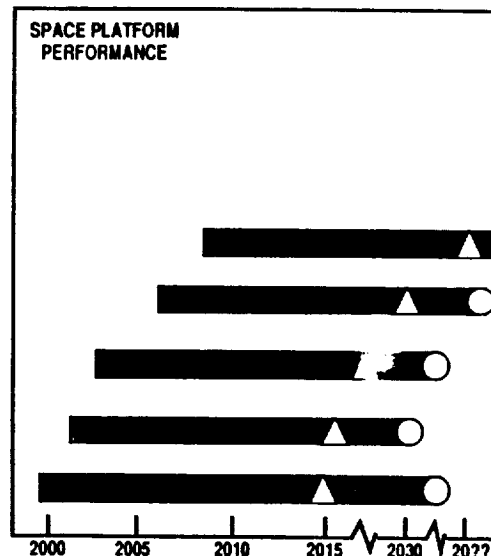
OAET

POWER AND THERMAL MANAGEMENT

NEW REGIME



5 - 7 YRS



15 - ? YRS

PT10-6

RC-ITP91 01-7 pm

SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS

(INCLUDES SPACE STATIONS)

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POWER AND THERMAL MANAGEMENT

DEDICATED vs UTILITY POWER SYSTEMS

REQUIREMENTS

CHARACTERISTIC	DEDICATED	UTILITY
Source Capacity	1 - 10 kW	kW - MW
Source Number	1 - 2	Multiple
Growth	No	Yes
Lifetime	Fixed	Extendible
Repairable	No	Yes
Load/Source Cap.	~ 1	>>1
Physical Size	Small	Large
Flexibility	Loads fixed	Loads vary
Manned	No	Yes

APPROACH

DEDICATED

FOCUS ON MEETING

- MISSION SPECIFIC REQUIREMENTS
- ADAPT EXISTING SPACECRAFT BUS

UTILITY

- FOCUS ON MAJOR SYSTEM ELEMENTS

- GENERAL REQUIREMENTS

- FUNCTIONS

- MUTUAL COMPATIBILITY

- COMBINE MODULAR ELEMENTS

- INCLUDE REQUIREMENTS FOR

- REPAIRS

- USER TRANSPARENCY

- EVOLUTIONARY DEVELOPMENT

UTILITY APPROACH INCREASES DDT&E COSTS
BUT BROADENS APPLICABILITY AND LOWERS LIFE CYCLE COSTS.

RCC-910.01.2

SPACE PLATFORMS TECHNOLOGY PROGRAM

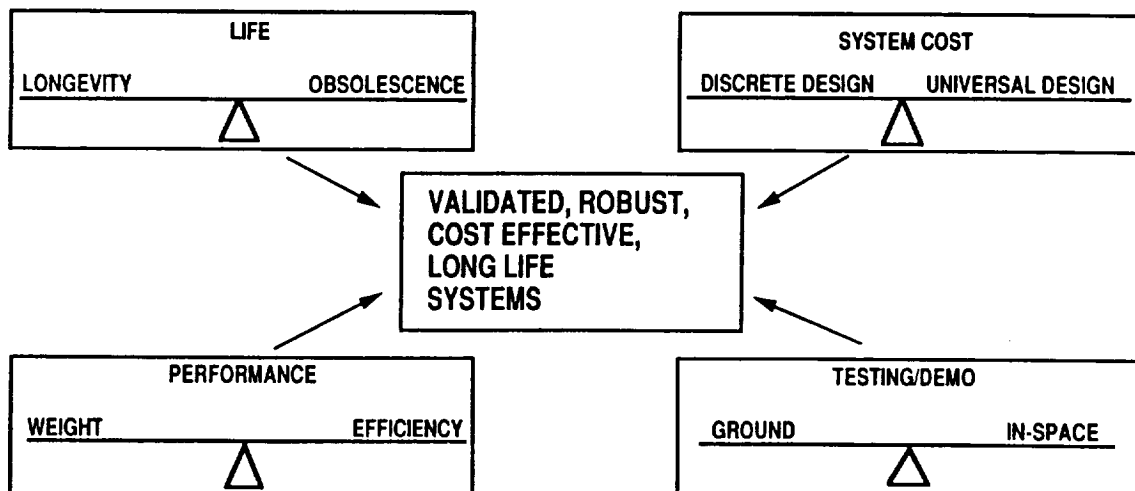
EARTH ORBITING PLATFORMS

(INCLUDES SPACE STATIONS)

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POWER AND THERMAL MANAGEMENT

TECHNOLOGY ASSESSMENT



SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS

(INCLUDES SPACE STATIONS)

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POWER AND THERMAL MANAGEMENT

PLAN

- FOCUS ON MISSIONS
- USE BASE PROGRAM TECHNOLOGY
- ENHANCE TECHNOLOGY DEVELOPMENT
 - TIMELINESS
 - DEVELOPMENT LEVEL
- DEMONSTRATE AT SYSTEMS LEVEL
- MOVE INTO FLIGHT PROGRAM

RC-ITP91 01-19 pm

SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS

(INCLUDES SPACE STATIONS)

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POWER AND THERMAL MANAGEMENT

SPACE RESEARCH AND TECHNOLOGY GOAL

TO ENSURE THE EFFECTIVE TRANSFER OF TECHNOLOGY TO MISSION APPLICATIONS BY CONDUCTING FOCUSED TECHNOLOGY PROGRAMS, WITH NEGOTIATED AND COORDINATED USER HAND-OFF AGREEMENTS WITH THE OTHER PROGRAM OFFICES IN NASA.

RC-ITP91 01-11 pm

SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS

(INCLUDES SPACE STATIONS)

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POWER AND THERMAL MANAGEMENT

OBJECTIVES

• Programmatic

Develop and demonstrate integrated power and thermal management technologies for near earth missions.

• Technical

- Reduce array area by 30% with 3X increased rad. tolerance
- 3X increase in battery energy density
- 2X reduction in PMAD system mass
- 2X reduction in radiator mass and area
- Extend lifetimes to 15-30 years

SCHEDULE

- 1996 - Demonstrate 300 W/kg planar PV, 100 W/kg InP concentrator module
- 1996 - Ground test cryogenic capillary pumped loop
- 1997 - Demonstrate advanced PMAD integrated avionics system
- 1997 - Ground demo, integrated 2 kW solar dynamic system
- 1998 - Demonstrate 1-2 kg/m² thermal management system
- 1998 - Complete advanced EPSAT
- 1999 - Demonstrate flight weight 100 Wh/kg battery
- 2000 - Demonstrate durable high temp. electronics subsystem (200-600 °C)

RESOURCES*

CURRENT

STRATEGIC

• 1991	---	---
• 1992	---	---
• 1993	---	\$ 5.1 M
• 1994	---	\$ 10.2 M
• 1995	---	\$ 13.5 M
• 1996	---	\$ 14.3 M
• 1997	---	\$ 14.7 M

*Includes both Earth Orbiting Platforms and Space Stations

PARTICIPANTS

• Goddard

Responsibility includes cryogenic bus technology and low temperature thermal management subsystems

• JPL

Responsibility includes lightweight planar PV and lithium battery technology and integrated PICs

• LeRC

Responsibility includes concentrator PV, InP cells, lightweight Ni/H₂ and Na/S, batteries moderate and high temperature radiators, integrated autonomous PMAD and high temperature electronics, solar dynamic system

RC-ITP91 01-1 pm

SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS

(INCLUDES SPACE STATIONS)

OAET

POWER AND THERMAL MANAGEMENT

OBJECTIVE

PROVIDE THE TECHNOLOGY TO MEET POWER SYSTEM REQUIREMENTS FOR FUTURE NEAR EARTH SPACE MISSIONS, INCLUDING GROWTH SPACE STATIONS AND EARTH ORBITING SPACECRAFT.

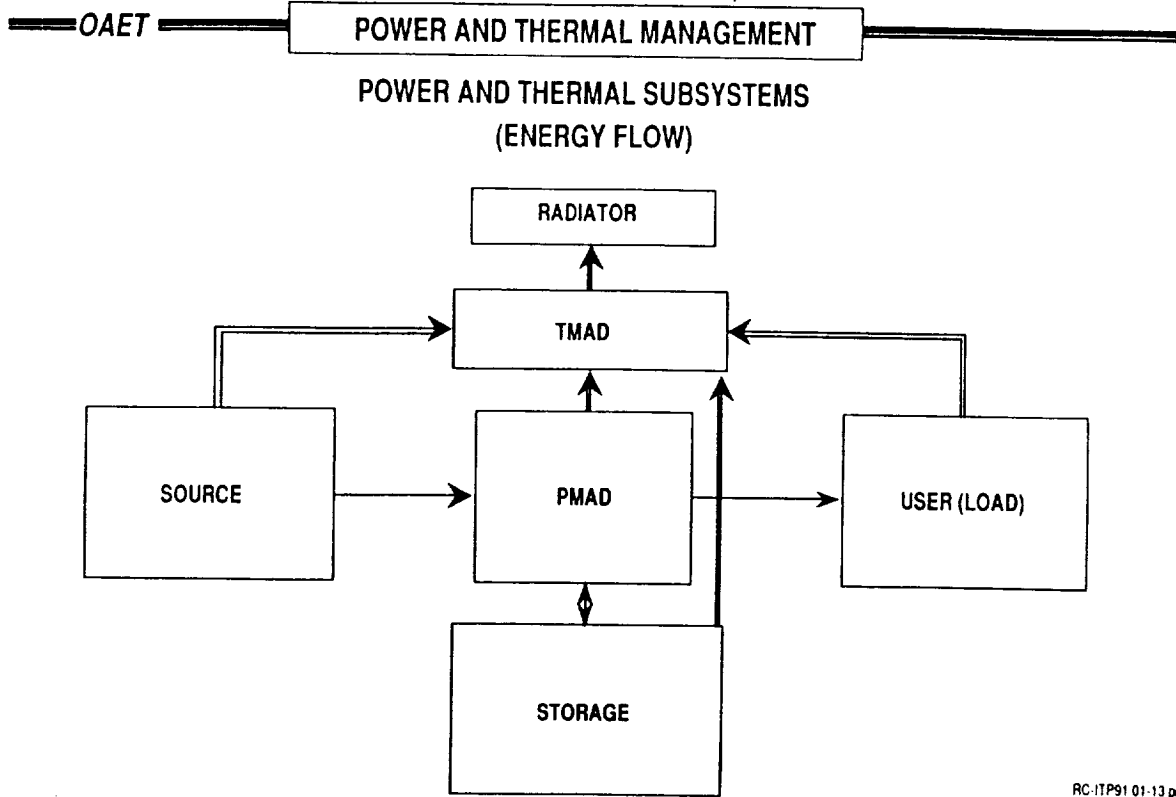
TECHNOLOGY AREAS:

- PHOTOVOLTAIC ENERGY CONVERSION (CELLS/ARRAYS)
- THERMAL ENERGY CONVERSION (SOLAR DYNAMIC)
- CHEMICAL ENERGY STORAGE (BATTERIES)
- POWER MANAGEMENT AND DISTRIBUTION
- THERMAL MANAGEMENT AND DISTRIBUTION

SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS

(INCLUDES SPACE STATIONS)



SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS

(INCLUDES SPACE STATIONS)



APPLICATIONS INVESTIGATED

EOS

TDRSS

SSF

SPACE PLATFORMS TECHNOLOGY PROGRAM

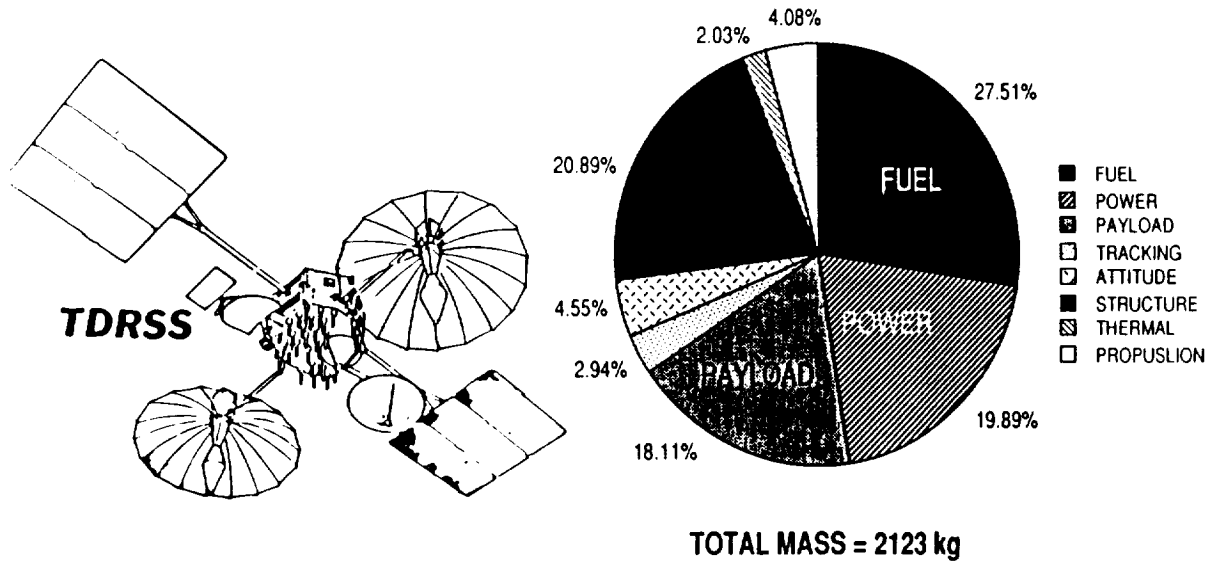
EARTH ORBITING PLATFORMS

(INCLUDES SPACE STATIONS)

OAET

POWER AND THERMAL MANAGEMENT

TRACKING AND DATA RELAY SATELLITE SYSTEM WET MASS



SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS

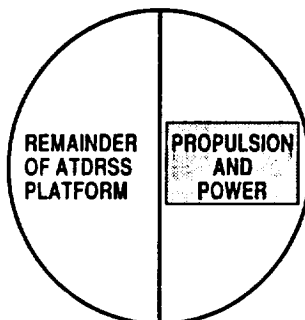
(INCLUDES SPACE STATIONS)

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POWER AND THERMAL MANAGEMENT

PROPULSION AND POWER DRIVERS ON ATRRSS

IMPROVEMENTS IN PROPULSION AND POWER CAN
SIGNIFICANTLY IMPROVE ATRRSS



PROPULSION AND POWER COMPRISE
ABOUT ONE-HALF OF THE TOTAL MASS
OF ATRRSS

A 2X IMPROVEMENT IN
PROPULSION AND POWER
WOULD DOUBLE THE
PAYLOAD ON ATRRSS

SPACE PLATFORMS TECHNOLOGY PROGRAM

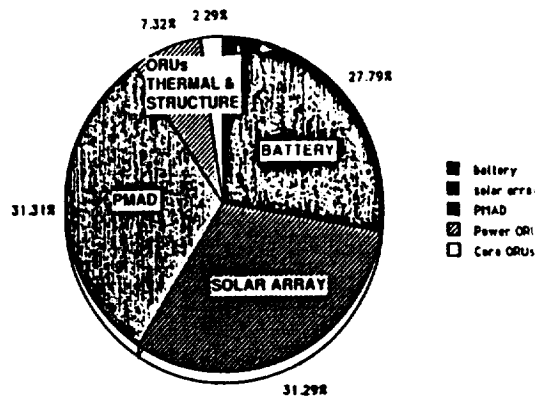
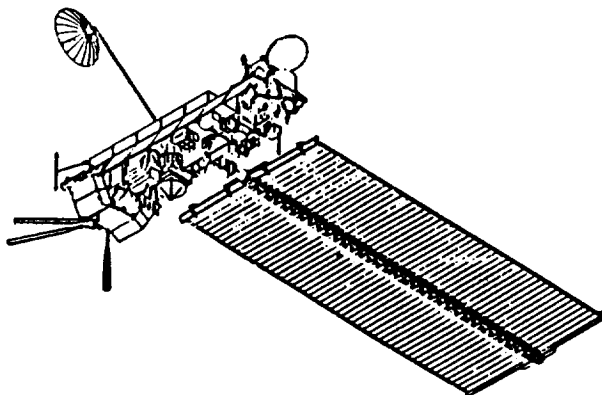
EARTH ORBITING PLATFORMS

(INCLUDES SPACE STATIONS)

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POWER AND THERMAL MANAGEMENT

ELECTRICAL POWER SYSTEM WEIGHTS



TOTAL EPS WEIGHT IS 3264.8 lbs (1484 kg)

SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS

(INCLUDES SPACE STATIONS)

OAET

POWER AND THERMAL MANAGEMENT

PHOTOVOLTAIC ENERGY CONVERSION

OBJECTIVE

PROVIDE THE TECHNOLOGY FOR PHOTOVOLTAIC ARRAYS WITH IMPROVED CONVERSION EFFICIENCY, REDUCED MASS, REDUCED COST, AND INCREASED OPERATING LIFE FOR ADVANCED SPACE MISSIONS

SPECIFIC LONG-RANGE GOALS ARE TO DEVELOP THE TECHNOLOGY BASE FOR PHOTOVOLTAIC ARRAYS WITH SPECIFIC POWER OF 300 W/kg WITH SUBSTANTIAL REDUCTIONS IN SIZE, COST, AND INCREASES IN END-OF-LIFE POWER CAPABILITY

TECHNOLOGY AREAS

- ADVANCED PHOTOVOLTAIC CELL TECHNOLOGY
- HIGH-PERFORMANCE ARRAYS
- HIGH-POWER ARRAYS

SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS

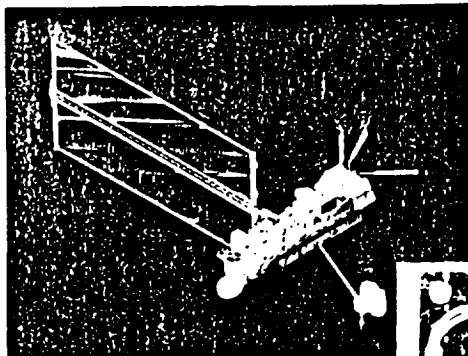
(INCLUDES SPACE STATIONS)

OAET

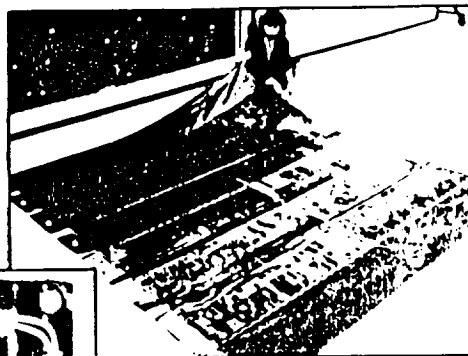
POWER AND THERMAL MANAGEMENT

EOS POWER TECHNOLOGY

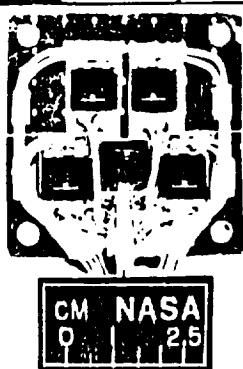
EOS (SAFE BASELINE)
29 W/Kg



APSA (Si)
77 W/Kg



ADVANCED
APSA (InP)
99 W/Kg



PV
CONCEPTS
FOR EOS
PLATFORMS

SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS

(INCLUDES SPACE STATIONS)

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POWER AND THERMAL MANAGEMENT

OBJECTIVE

TO DEVELOP AN ULTRA-LIGHT-WEIGHT, HIGH PERFORMANCE, ADVANCED
DEPLOYABLE PHOTOVOLTAIC ARRAY DESIGN THAT WILL BE SUITABLE FOR A
BROAD RANGE OF LONG-TERM NASA AND U.S. COMMERCIAL SPACE
APPLICATIONS FOR THE PERIOD BEYOND 1990

NEAR-TERM SPECIFIC POWER: 130 W/kg^{*}
LONG-TERM SPECIFIC POWER: 300 W/kg^{*}

^{*}BOL ARRAY POWER FOR GEO

SPACE PLATFORMS TECHNOLOGY PROGRAM

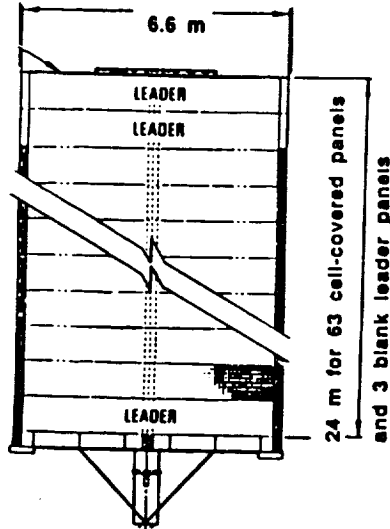
EARTH ORBITING PLATFORMS
(INCLUDES SPACE STATIONS)

OAET

POWER AND THERMAL MANAGEMENT

APSA ARRAY FOR EOS

- Thin silicon cells, 13.5% eff
- Retractable
- Carbon-loaded Kapton blanket
- Graphite/epoxy structure
- Fiberglass boom
- Aluminum canister



$P_{EOL} = 13,136 \text{ W}$
(5 year/705 km/98 deg Incl.)

Performance

Without Solar Array Drive Assembly (SADA)

Specific Power = 96 W/kg
Power Density = 94 W/m² > 10% cont.

Specific Power = 88 W/kg
Power Density = 94 W/m² > 20% cont.

With SADA/Boom (27 kg allocation)

Specific Power = 84 W/kg
Power Density = 94 W/m² > 10% cont.

Specific Power = 77 W/kg
Power Density = 94 W/m² > 20% cont.

AREA ABOUT 82% OF
EOS ARRAY AREA

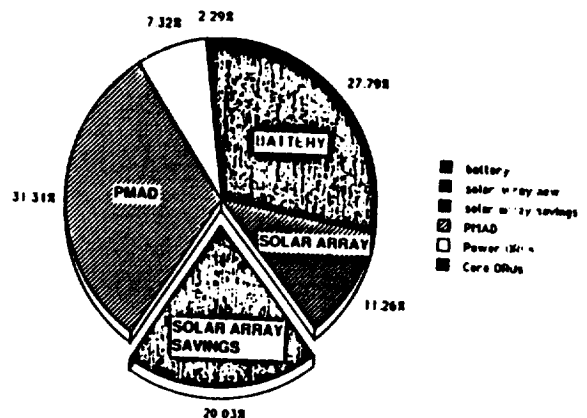
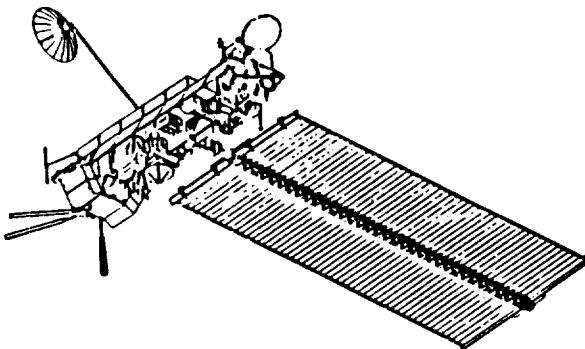
SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS
(INCLUDES SPACE STATIONS)

OAET

POWER AND THERMAL MANAGEMENT

ELECTRIC POWER SYSTEM WEIGHTS



ADVANCED PHOTOVOLTAIC SOLAR ARRAY (APSA)
SAVES 297.3 kg (654 lb)

SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS

(INCLUDES SPACE STATIONS)

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POWER AND THERMAL MANAGEMENT

ADVANCED PHOTOVOLTAIC SOLAR ARRAY

- **GOAL: 10X IMPROVEMENT IN PHOTOVOLTAIC ARRAY DESIGN**
 - ACHIEVED NEAR-TERM GOAL OF 130 W/kg
 - WORKING TOWARD LONG-TERM GOAL OF 300 W/kg
- **LABORATORY VERIFICATION WITH PROTOTYPE BLANKET ASSEMBLY AND LIGHT-WEIGHT MAST SYSTEM**
 - 2X IMPROVEMENT OVER SAFE ARRAY AND 3X-4X IMPROVEMENT OVER CURRENT RIGID-PANEL ARRAYS
- **PLAN TO COMPLETE PROTOTYPE COMPONENTS AND CONDUCT FUNCTIONAL TESTS**

ACTIVE INVOLVEMENT OF USERS WILL ENSURE TIMELY COMPLETION TO MEET LAUNCH DATES

RC-ITP91 01-84 pm

SPACE PLATFORMS TECHNOLOGY PROGRAM

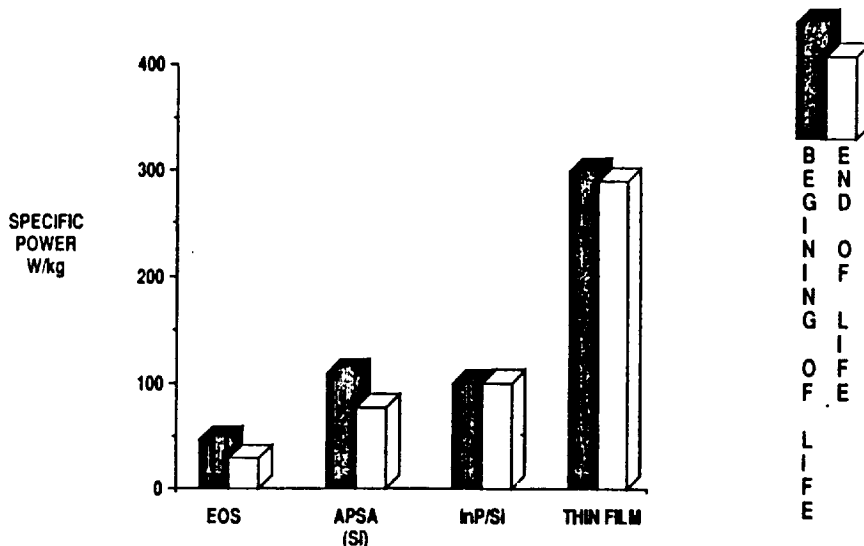
EARTH ORBITING PLATFORMS

(INCLUDES SPACE STATIONS)

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POWER AND THERMAL MANAGEMENT

EVOLUTION OF PLANAR ARRAY SPECIFIC POWER



RC-ITP91 01-22 pm

SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS

(INCLUDES SPACE STATIONS)

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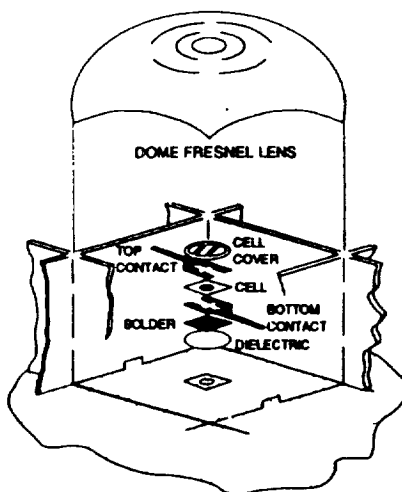
POWER AND THERMAL MANAGEMENT

CONCENTRATOR TECHNOLOGY

LeRC

MINI-DOME FRESNEL LENS
CONCENTRATOR ELEMENT

POWER
TECHNOLOGY
DIVISION



RC-ITP91 01-46 pm

SPACE PLATFORMS TECHNOLOGY PROGRAM

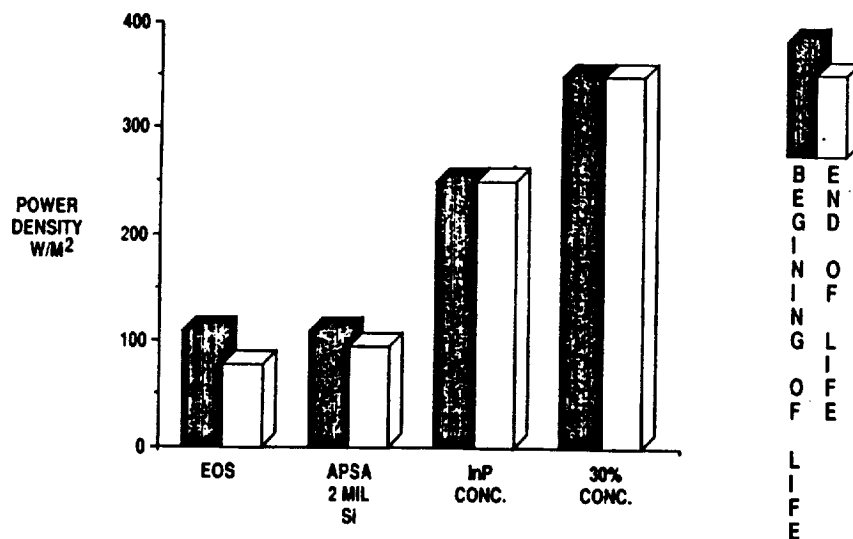
EARTH ORBITING PLATFORMS

(INCLUDES SPACE STATIONS)

OAET

POWER AND THERMAL MANAGEMENT

EVOLUTION OF ARRAY POWER DENSITY



RC-ITP91 01-23 pm

SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS

(INCLUDES SPACE STATIONS)

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POWER AND THERMAL MANAGEMENT

Project Overview and Resources

Technology Program: Space Platforms
Technology Area: Earth Orbiting Platforms
Technology Element: Power
Technology Sub-Element: Power Generation (Photovoltaic)

WBS No.: 694-11-05

Milestones:

1996 300 w/kg planar blanket fabricated
1996 100 w/kg InP concentrator panel demo
1998 Demo thin film cell array > 300 w/kg
1998 Demo 50 w InP concentrator module through environmental testing

	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
R&D Resources:	0	0	0.6	1.3	1.9	2.3	2.5	3.3	0	0
C of F (\$M):	0	0	0	0	0	0	0	0	0	0

SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS

(INCLUDES SPACE STATIONS)

OAET

POWER AND THERMAL MANAGEMENT

CHEMICAL ENERGY CONVERSION

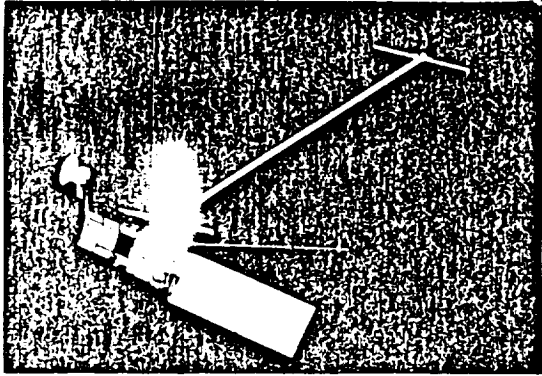
OBJECTIVES

PROVIDE THE TECHNOLOGY BASE FOR ADVANCED ELECTROCHEMICAL ENERGY CONVERSION AND STORAGE SYSTEMS REQUIRED TO SUPPORT THE LOW TO HIGH POWER NEEDS OF FUTURE MANNED AND UNMANNED SPACE APPLICATIONS, THE CYCLE LIFE REQUIREMENTS OF LOW-EARTH-ORBIT (LEO) SYSTEMS

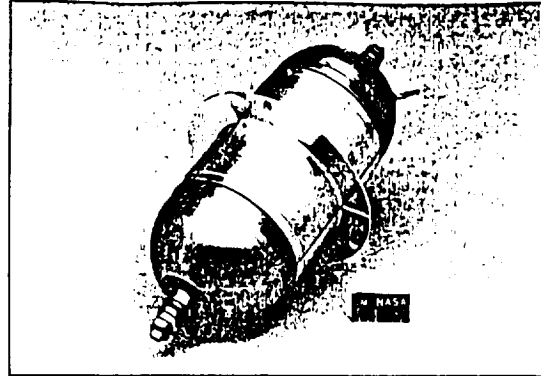
TECHNOLOGY AREAS

- SECONDARY BATTERIES
- ADVANCED ELECTROCHEMICAL ENERGY STORAGE

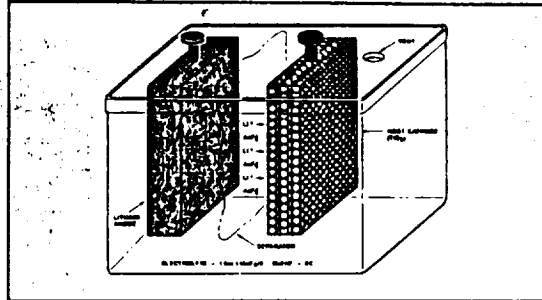
PROGRESS IN ENERGY STORAGE



EOS Nickel-Hydrogen
(10 W-hr/Kg)



Advanced Nickel-Hydrogen
(24 W-hr/Kg)



Future Applications
Chemical Energy Storage
(**>40 W-hr/Kg**)

RP88 415

SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS
(INCLUDES SPACE STATIONS)

OAET

POWER AND THERMAL MANAGEMENT

LIGHT-WEIGHT NiH_2 CELLS NEAR-TERM ADVANCEMENT OF PROVEN TECHNOLOGY

OBJECTIVES

- IMPROVED SPECIFIC ENERGY CELLS
- IMPROVED SPECIFIC VOLUME CELLS

APPROACH

- COMPUTER-AIDED DESIGN OPTIMIZATION
- TECHNOLOGY DEVELOPMENT
 - LIGHT-WEIGHT NICKEL ELECTRODE
 - OPTIMIZATION OF KOH CONCENTRATION
- VERIFICATION TESTING VIA BOILER PLATE AND FLIGHT-WEIGHT CELLS

SPACE PLATFORMS TECHNOLOGY PROGRAM

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POWER AND THERMAL MANAGEMENT

LIGHT-WEIGHT NiH_2 CELLS NEAR-TERM ADVANCEMENT OF PROVEN TECHNOLOGY

(Continued)

GOALS

- 2.0 x SOA SPECIFIC ENERGY
- 1.2 x SOA SPECIFIC VOLUME
- ENHANCED LEO AND GEO MISSIONS, SUCH AS:
 - SSF
 - PLATFORMS
 - SPACE TELESCOPE
 - COMMUNICATION SATELLITES

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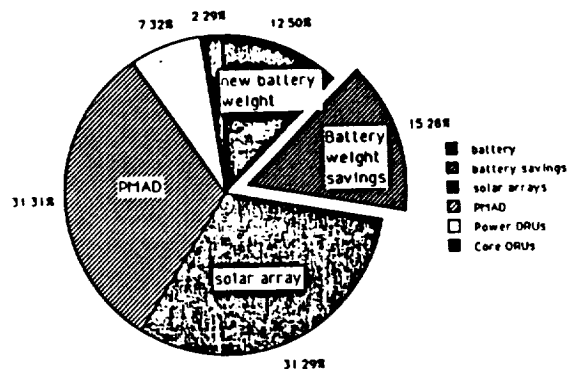
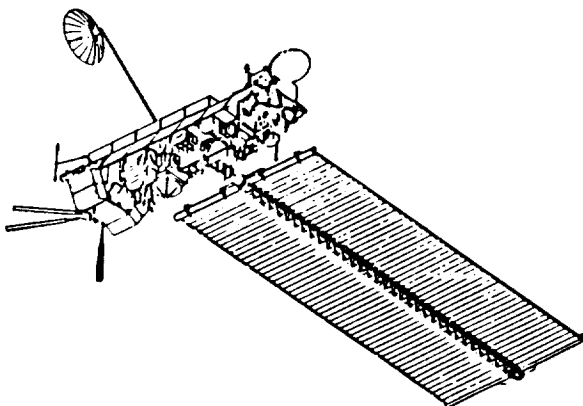
SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS
(INCLUDES SPACE STATIONS)

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POWER AND THERMAL MANAGEMENT

ELECTRICAL POWER SYSTEM WEIGHTS



ADVANCED BATTERY TECHNOLOGY CAN SAVE ~227 kg (~500 lb)

SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS

(INCLUDES SPACE STATIONS)

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POWER AND THERMAL MANAGEMENT

Project Overview and Resources

Technology Program: Space Platforms
Technology Area: Earth Orbiting Platforms
Technology Element: Power
Technology Sub-Element: Energy Storage

WBS No.: 694-11-06

Milestones:

1995 Demo 100 Wh/kg boilerplate cells to 1000+ cycles (GEO) (Li and Ni/H₂)
1997 Define engineering model components for 150 Wh/kg battery
1999 Demo 100 Wh/kg flightweight battery
2000 Demo 150 Wh/kg (engineering model)

	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
R&D Resources:	0	0	0.7	1.2	1.6	1.6	1.4	1.4	0	0
C of E (\$M):	0	0	0	0	0	0	0	0	0	0

SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS

(INCLUDES SPACE STATIONS)

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POWER AND THERMAL MANAGEMENT

THERMAL ENERGY CONVERSION

OBJECTIVES

- DEVELOP THE TECHNOLOGY BASE TO PROVIDE ADVANCED HIGH-EFFICIENCY, HIGH-TEMPERATURE (1050 - 1400 K), LONG-LIFE SOLAR DYNAMIC STIRLING/BRAYTON POWER SYSTEM FOR A WIDE RANGE OF NASA AND COMMERCIAL SPACE POWER NEEDS

TECHNOLOGY AREAS

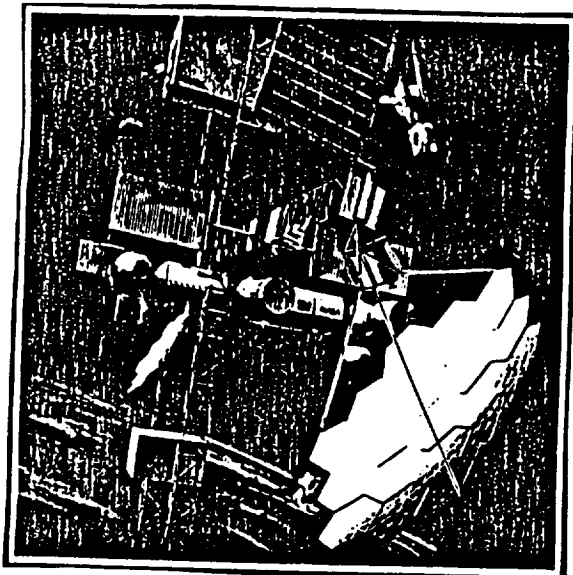
- HIGH-TEMPERATURE SOLAR DYNAMICS

POWER AND THERMAL MANAGEMENT

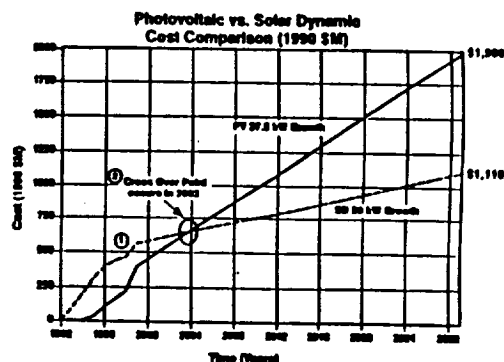
THERMAL ENERGY CONVERSION

MISSION & BENEFITS
- EARTH ORBITING PLATFORMS -

SPACE STATION FREEDOM

QUALITATIVE BENEFITS

- MORE FLEXIBILITY
- LONG LIFE COMPONENTS
- LESS DRAG
- LOWER MASS
- LOWER RECURRING COSTS
- LESS AGGREGATE EVA

QUANTITATIVE BENEFITS

C91-001.4

SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS

(INCLUDES SPACE STATIONS)

POWER AND THERMAL MANAGEMENT

TECHNOLOGY ISSUES

SYSTEM LEVEL

- SOLAR DYNAMIC SYSTEM INTERACTIONS
- SCALABILITY
- POWER SHARING (AC & DC) SOURCES

SUBSYSTEM LEVEL

- | | |
|---|--|
| <ul style="list-style-type: none"> • CONCENTRATOR <ul style="list-style-type: none"> - FABRICATION PROCESSES - OPTICS - DEPLOYMENT • PCU <ul style="list-style-type: none"> - START-UP - TRANSIENT OPERATION - OFF-DESIGN OPERATION | <ul style="list-style-type: none"> • HEAT RECEIVER <ul style="list-style-type: none"> - HOT SPOTS - THERMAL RATCHETING • RADIATOR <ul style="list-style-type: none"> - NONE • CONTROLS <ul style="list-style-type: none"> - PARALLEL OPERATION - LOAD FOLLOWING |
|---|--|

SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS

(INCLUDES SPACE STATIONS)

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POWER AND THERMAL MANAGEMENT

SOLAR DYNAMICS 2 kW GROUND TEST EXPERIMENT						
ELEMENT	FISCAL YEAR					
	91	92	93	94	95	96
1. PROCUREMENT						
2. SYSTEM DESIGN & INTEGRATION						
3. CONCENTRATOR						
- DESIGN						
- ENGR. DEVELOPMENT						
- FABRICATION						
- TEST						
4. HEAT RECEIVER						
- DESIGN						
- ENGR. DEVELOPMENT						
- FABRICATION						
- TEST						
5. PCU REFURBISH & TEST						
6. TEST SUPPORT EQUIPMENT						
- DESIGN						
- ENGR. DEVELOPMENT						
- FABRICATION						
7. INTEGRATED SUBSYSTEMS TESTS						
8. SYSTEM INTERACTION TESTS						

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EARTH ORBITING PLATFORMS

(INCLUDES SPACE STATIONS)

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POWER AND THERMAL MANAGEMENT

Project Overview and Resources

Technology Program: Space Platforms
Technology Area: Earth Orbiting Platforms
Technology Element: Power
Technology Sub-Element: Power Generation (Solar Dynamic)

WBS No.: 694-11-02

Milestones:

1994 Select Brayton or Stirling PCU
 1995 Demo 30% efficient concentrator cascade cell
 1997 Demo 300 W/m² refractive concentrator PV module (750 W)
 1997 Ground demo 2 kW advanced solar dynamic system
 1999 Identify system level SD issues

	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
R&D Resources:	0	0	1.2	3.5	3.6	3.4	3.0	1.9	0	0
C of F (\$M):	0	0	0	0	0	0	0	0	0	0

SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS
(INCLUDES SPACE STATIONS)

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POWER AND THERMAL MANAGEMENT

POWER MANAGEMENT

OBJECTIVES

- DEVELOP THE ELECTRICAL POWER SYSTEMS CONDITIONING, CONTROL, AND DISTRIBUTION TECHNOLOGY NEEDED FOR EARTH ORBITAL SPACE MISSIONS

TECHNOLOGY AREAS

- HIGH-VOLTAGE, HIGH-POWER SYSTEMS
- HIGH-DENSITY POWER SYSTEMS
- FAULT TOLERANT/POWER INTEGRATED CIRCUITS

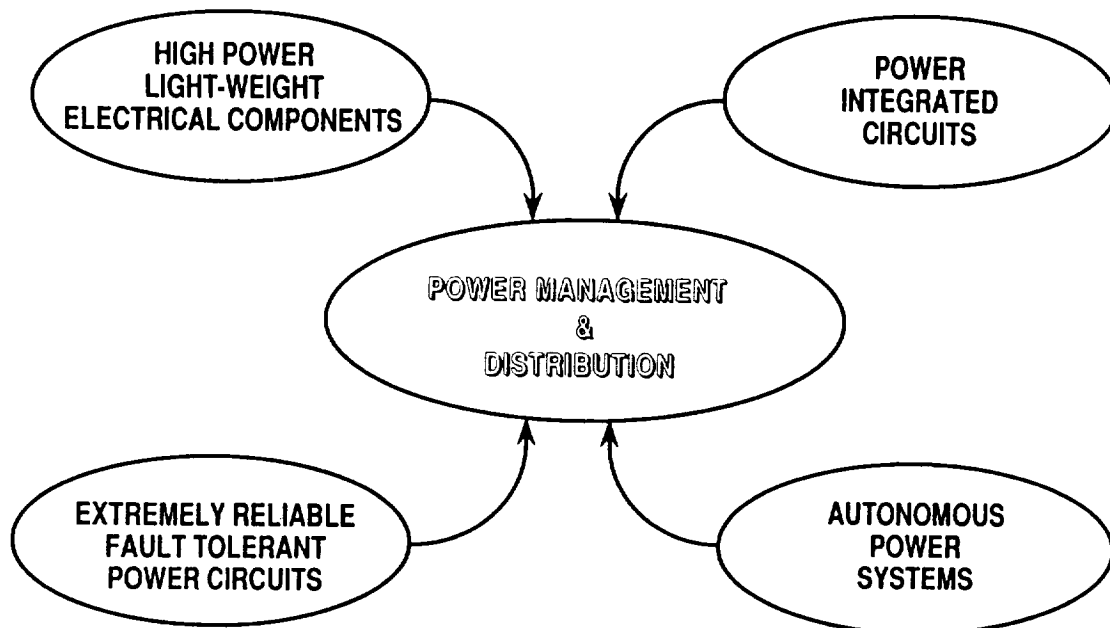
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(INCLUDES SPACE STATIONS)

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POWER AND THERMAL MANAGEMENT



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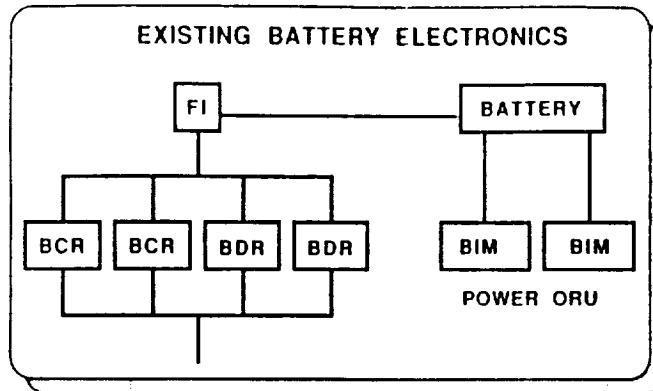
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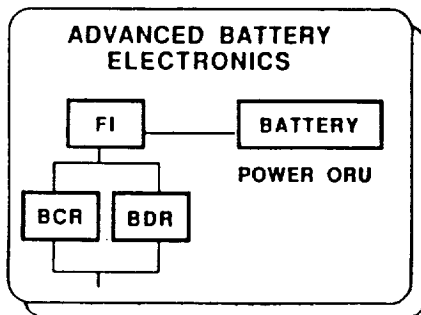
EARTH ORBITING PLATFORMS (INCLUDES SPACE STATIONS)

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POWER AND THERMAL MANAGEMENT



ASSEMBLY	MASS (LBS.)
2ea BCR	26
2ea BDR	52
2ea BIM	6
TOTAL PER POWER ORU	84



ASSEMBLY	MASS (LBS.)
2ea BDC	34

SIGNIFICANCE

EOS POWER SYSTEM MASS SAVINGS
50lbs PER POWER ORU OR 200lbs PER PLATFORM.

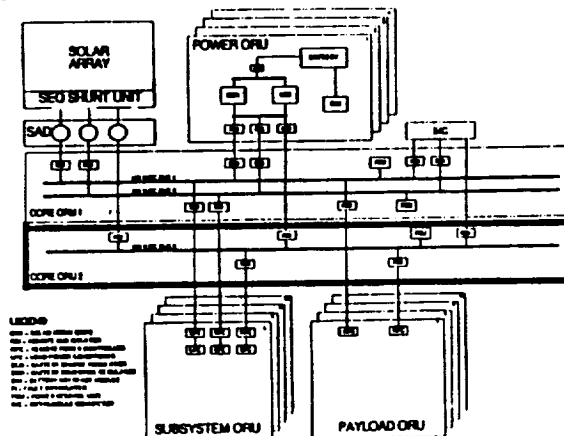
SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS (INCLUDES SPACE STATIONS)

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POWER AND THERMAL MANAGEMENT

POWER SUBSYSTEM BLOCK DIAGRAM



FAULT TOLERANCE SAVINGS

REDUCE NUMBER OF POWER BUSES FROM THREE TO TWO

- 2 LPCs 4.4 lbs
- 3 RPCs 2.3 lbs
- 1 PCU 6.5 lbs
- 15 RBIs 30.0 lbs
- ORU HARNESS 16.0 lbs

TOTAL SAVINGS 59.2 lbs (27 kgs)

NOTE: ORU #2 MAY BE ABLE TO BE ELIMINATED ENTIRELY, DEPENDING ON THERMAL CONSIDERATIONS.
IF ORU IS ELIMINATED ENTIRELY, THE WEIGHT SAVINGS WOULD BE 210 lbs (95 kgs)

SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS
(INCLUDES SPACE STATIONS)

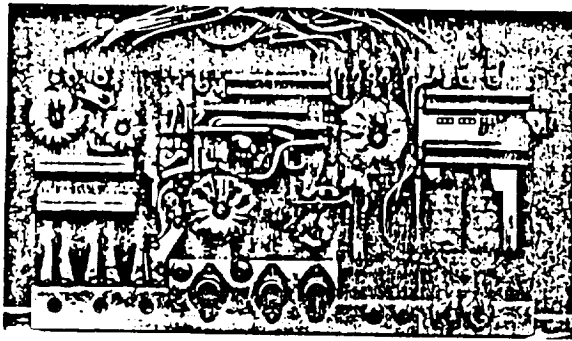
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POWER AND THERMAL MANAGEMENT

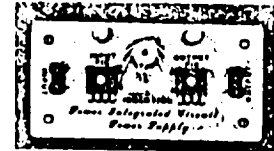
HIGH DENSITY POWER/POWER INTEGRATED CIRCUITS

Goal: Achieve high density power technologies of 10 W/in.³ by year 2000

STATE OF THE ART
DISCRETES: VOLUME/MASS INTENSIVE



100 W
30 V
dc S/C
POWER SUPPLY



IMPACT: 80% MASS REDUCTION
80% VOLUME REDUCTION
89% PARTS REDUCTION
50% LOSS REDUCTION

Plan: Hold power system to 20% of total system

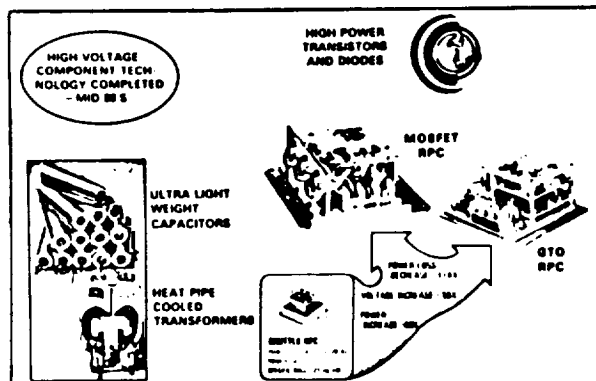
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EARTH ORBITING PLATFORMS
(INCLUDES SPACE STATIONS)

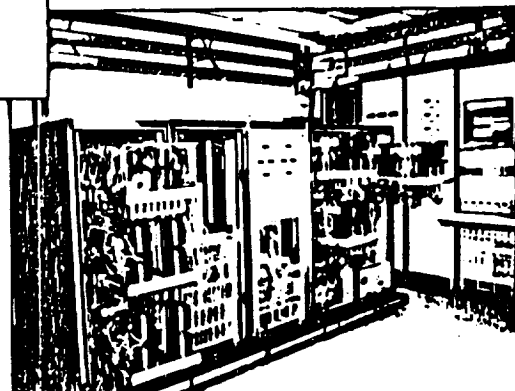
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POWER AND THERMAL MANAGEMENT

HIGH FREQUENCY POWER TECHNOLOGY



SPACE STATION
FREEDOM
PMAD TEST BED



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EARTH ORBITING PLATFORMS

(INCLUDES SPACE STATIONS)

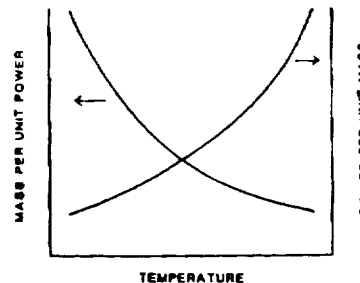
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POWER AND THERMAL MANAGEMENT

HIGH TEMPERATURE POWER TECHNOLOGY

GOALS

- REDUCE RADIATOR WEIGHT IN SPACE SYSTEMS BY RAISING OPERATING TEMPERATURE FROM 100°C TO 300°C
- HOSTILE ENVIRONMENT TOLERANCE
- IMPROVE RELIABILITY AND LIFETIME
- HIGHER ENERGY DENSITIES
- LESS THERMAL MANAGEMENT REQUIREMENTS
- REDUCE LAUNCH COST



TECHNOLOGICAL DEVELOPMENTS

- ADVANCED MATERIALS: DIELECTRICS, INSULATION, SEMICONDUCTOR, MAGNETICS
- COMPONENTS: CAPACITORS, INDUCTORS, SWITCHES, TRANSISTORS, CABLES, TRANSFORMERS, CIRCUIT BOARDS, INVERTERS, GENERATORS, COMPUTERS

APPLICATIONS

- SPACE EXPLORATION AND DOD SYSTEMS
- SPACE NUCLEAR POWER
- ADVANCED AND CONVENTIONAL AIRCRAFT



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SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS

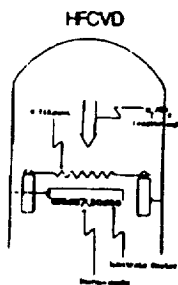
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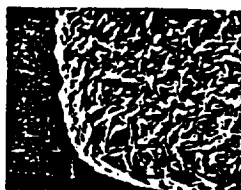
POWER AND THERMAL MANAGEMENT

CVD DIAMOND FILMS FOR HIGH POWER ELECTRONICS

SYNTHESIS

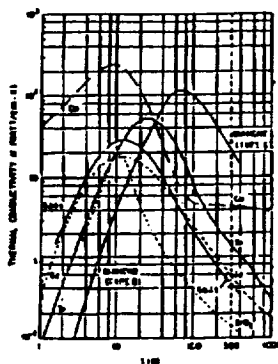


Polycrystalline CVD Diamond

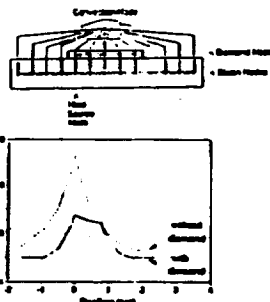


CHARACTERIZATION

Thermal Conductivity



& MODELLING



OF CVD DIAMOND

WILL ENABLE:

- More Efficient Heat Spreaders
- Lower Device Operating Temperatures
- Increased Device Reliability/Lifetime
- Increased Specific Power
- Elaborate Device Geometries

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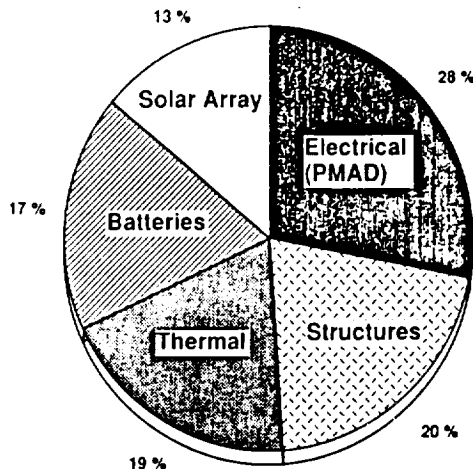
EARTH ORBITING PLATFORMS

(INCLUDES SPACE STATIONS)

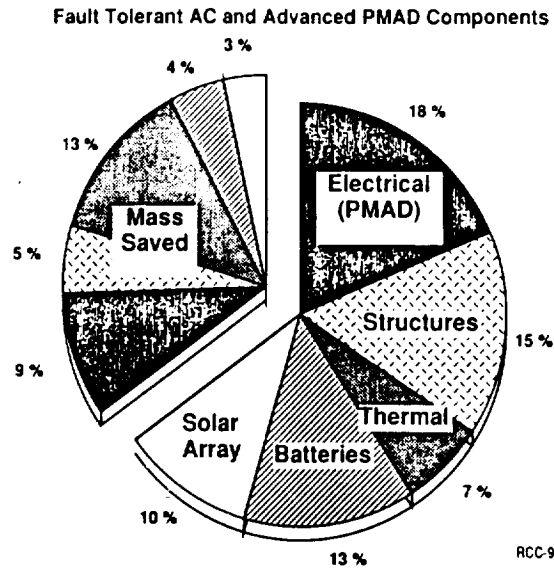
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POWER AND THERMAL MANAGEMENT

Efficient, High Temperature Power for Growth Station



Present Power System Masses



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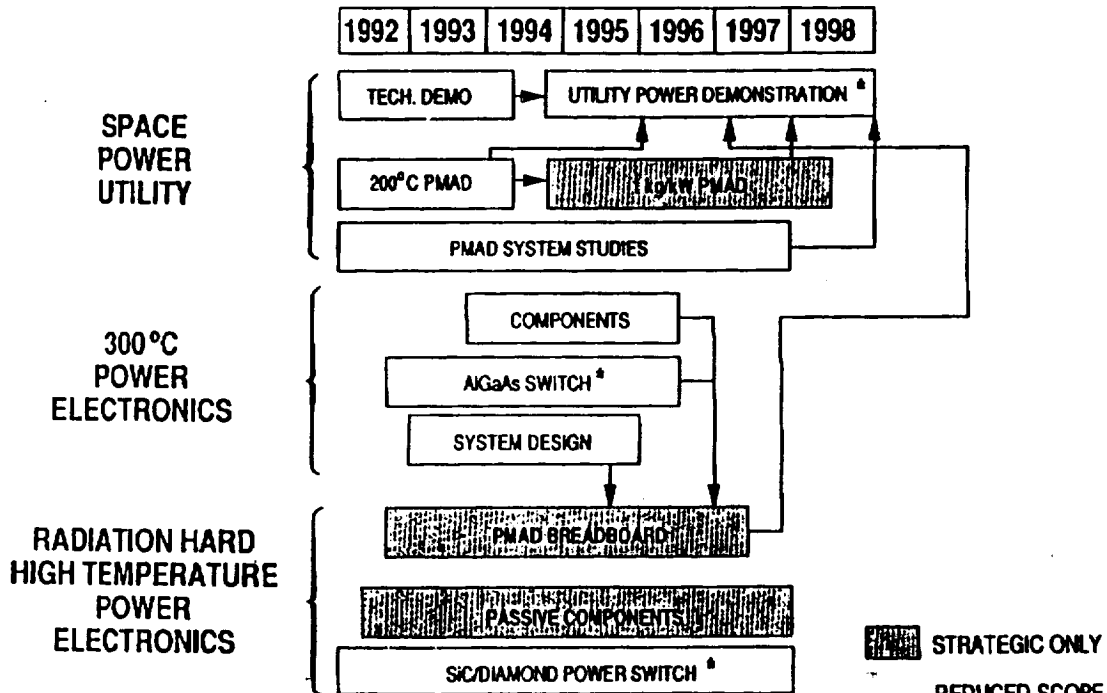
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(INCLUDES SPACE STATIONS)

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POWER AND THERMAL MANAGEMENT

SPACE-UTILITY/HIGH TEMPERATURE PMAD ROADMAP/SCHEDULE



SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS

(INCLUDES SPACE STATIONS)

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POWER AND THERMAL MANAGEMENT

Project Overview and Resources

Technology Program: Space Platforms
 Technology Area: Earth Orbiting Platforms
 Technology Element: Power
 Technology Sub-Element: Power Mgmt & Control (Solar Dynamic)

WBS No.: 694-11-03

Milestones:

1994 Select PMAD architecture
 1996 Demo prototype PMAD brassboard
 1997 Demo mixed source operation
 1998 Complete PMAD tested
 1999 Demo autonomous control, fault tolerance, and reconfiguration

	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
R&D Resources:	0	0	0.4	0.8	1.2	1.2	1.3	1.2	0	0
C of F (\$M):	0	0	0	0	0.2	0.2	0.3	0	0	0

SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS

(INCLUDES SPACE STATIONS)

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POWER AND THERMAL MANAGEMENT

Project Overview and Resources

Technology Program: Space Platforms
 Technology Area: Earth Orbiting Platforms
 Technology Element: Power
 Technology Sub-Element: Power Managemt. & Control (Photovoltaic)

WBS No.: 694-11-07

Milestones:

1994 Select PMAC architectures; demo GIC EMI shielded electronics box
 1995 Demo smart, long life components (PIC and other)
 1996 Demo monolithic circuits
 1997 Demo fault tolerant PMAC breadboard
 1997 Demo 200-600 C components/circuits
 1998 Advanced EPSAT code
 1999 Demo smart power backbone avionics system

	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
R&D Resources:	0	0	1.2	2	2.9	3.5	4.1	3.9	0	0
C of F (\$M):	0	0	0	0	0	0.3	0.3	0.4	0	0

SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS

(INCLUDES SPACE STATIONS)

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POWER AND THERMAL MANAGEMENT

THERMAL MANAGEMENT

OBJECTIVES

- DEVELOP THE THERMAL MANAGEMENT TECHNOLOGY FOR ADVANCED HIGH CAPACITY AND HIGH PERFORMANCE THERMAL MANAGEMENT SYSTEMS FOR FUTURE NASA SPACE MISSIONS
- ENHANCE THE UNDERSTANDING OF FLUID BEHAVIOR AND DYNAMICS IN A REDUCED GRAVITY ENVIRONMENT TO ESTABLISH RELIABLE PREDICTIVE MODELS AND DATA BASES FOR THE DEVELOPMENT OF ADVANCED SPACE SYSTEMS. INTERESTS INCLUDE TWO-PHASE FLOW REGIME, LIQUID/VAPOR INTERFACES AND FLOW BOILING
- DEVELOP, ANALYZE, AND TEST VARIOUS THERMAL ENERGY MANAGEMENT CONCEPTS AND COMPONENTS FOR APPLICATION TO FUTURE SPACECRAFT AND SPACE FACILITIES

TECHNOLOGY AREAS

- FILM CONDENSATION, FLOW BOILING AND TWO-PHASE REGIMES
- HEAT PIPES
- ADVANCED RADIATORS
- HEAT PUMPS

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SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS

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POWER AND THERMAL MANAGEMENT

THERMAL MANAGEMENT

- THE THERMAL MANAGEMENT SUB-ELEMENT WILL SUPPORT THE PLATFORM POWER AND THERMAL MANAGEMENT BY PURSUING AN INTEGRATED PROGRAM WHICH FOCUSES ON THE FOLLOWING ACTIVITIES:
 - MODULAR HEAT PUMPS (100 W TO 1 kW)
 - CRYOGENIC HEAT PIPES (60 - 80 K RANGE)
 - LIGHTWEIGHT MATERIALS
 - MINI CAPILLARY PUMPED LOOPS (<500 W)

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EARTH ORBITING PLATFORMS

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POWER AND THERMAL MANAGEMENT

BENEFITS TO SPACE STATION

- THERMAL MANAGEMENT -

THE THERMAL MANAGEMENT TECHNOLOGIES DEVELOPED IN THIS ACTIVITY WILL PROVIDE THE FOLLOWING BENEFITS:

- HEAT PUMPS - AS AN INTERMEDIARY BETWEEN A CENTRAL THERMAL BUS AND A LOAD, A HEAT PUMP COULD ALLOW INDEPENDENT TEMPERATURE CONTROL. THE SECOND, LOWER TEMPERATURE BUS, WOULD NOT BE NEEDED. ALTERNATIVELY, LOWER TEMPERATURES ARE POSSIBLE.
- CRYOGENIC HEATS PIPES - THESE COULD SERVE AS AN INTERFACE BETWEEN CRYOGENIC SENSORS AND A CENTRAL BANK OF CRYOCOOLERS. THE NUMBER OF SUCH COOLERS NEEDED WOULD THUS BE REDUCED, AND THEIR ASSOCIATED VIBRATION AND EMI SEPARATED FROM THE SENSORS.
- LIGHT-WEIGHT MATERIALS - WEIGHT REDUCTION
- MINI CAPILLARY PUMPED LOOPS - COULD PROVIDE INDEPENDENT COOLING FOR INSTRUMENTS

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SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS

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POWER AND THERMAL MANAGEMENT

Project Overview and Resources

Technology Program: Space Platforms
Technology Area: Earth Orbiting Platforms
Technology Element: Power
Technology Sub-Element: Thermal Management (Photovoltaic)

WBS No.: 694-11-01

Milestones:

1994	Demo mini CPL thermal control loop
1995	Demo 50% improvement (wall-meter basis) in advanced cryoheat pipes on ground
1995	Demo 33% weight reduction in thermal components by using lightweight materials
1996	Demo advanced heat pump designs suitable for micro gravity applications, with goal of 3x current performance factor
1996	Design cryo CPL thermal control loop
1997	Flight test advanced cryo heat pipes
1997	Demo ground test of advanced cryo CPL
1998	Validate cryo heat pipe models
1998	Flight test advanced heat pumps
1999	Validate heat pump models
2000	Flight test cryo CPL thermal control loop

	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
R&D Resources:	0	0	0.8	0.8	1.3	1.3	1.4	1.3	0	0
C of F (\$M):	0	0	0	0	0.5	0.2	0	0	0	0

SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS (INCLUDES SPACE STATIONS)

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POWER AND THERMAL MANAGEMENT

Project Overview and Resources

Technology Program: Space Platforms
Technology Area: Earth Orbiting Platforms
Technology Element: Power
Technology Sub-Element: Thermal Management (Solar Dynamic)

WBS No.: 694-11-04

Milestones:

1994 Demo mini CPL thermal control loop
1995 Demo 50% improvement for advanced cryoheat pipes in ground test
1995 Demo 33% weight reduction for thermal components made from lightweight materials
1996 Demo advanced heat pump (for 500 W-5 kW range), 3X performance improvement
1997 Flight test cryoheat pipes
1997 Demo ground test of cryo CPL ground loop
1998 Validate cryo heat pipe models
1998 Flight test of advanced heat pumps
1999 Validate heat pump models
2000 Flight test of cryo CPL thermal loop

	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
R&D Resources:	0	0	0.4	0.6	1.0	1.0	1.0	1.0	0	0
C of F (\$M):	0	0	0	0	0.1	0.3	0.3	0	0	0

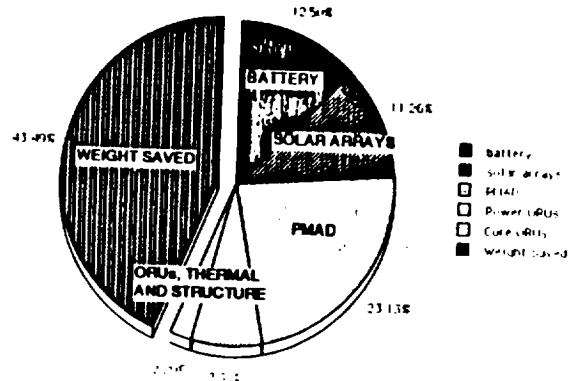
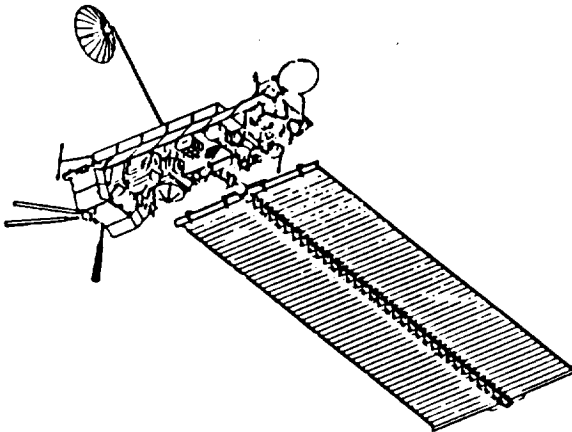
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EARTH ORBITING PLATFORMS (INCLUDES SPACE STATIONS)

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POWER AND THERMAL MANAGEMENT

ELECTRICAL POWER SYSTEM WEIGHTS WITH ADVANCED TECHNOLOGIES



**ADVANCED POWER SYSTEM TECHNOLOGIES CAN SAVE
645 kg (1420 lb) IN THE ELECTRICAL POWER SYSTEM**

SPACE PLATFORMS TECHNOLOGY PROGRAM

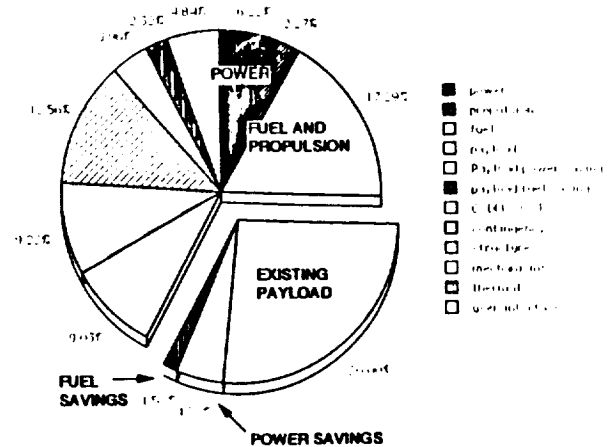
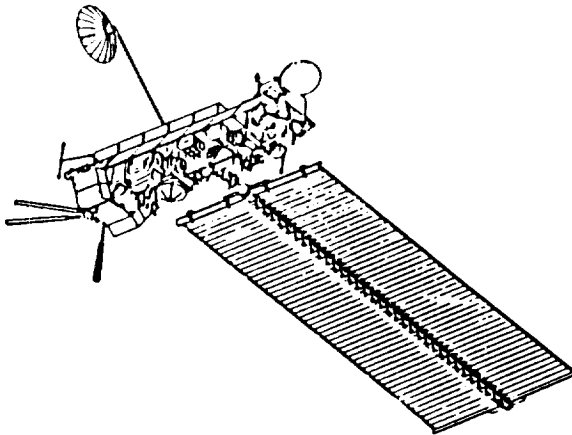
EARTH ORBITING PLATFORMS

(INCLUDES SPACE STATIONS)

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POWER AND THERMAL MANAGEMENT

POLAR PLATFORM WEIGHT WITH ADVANCED TECHNOLOGIES



**NEW TECHNOLOGIES SAVE 850 Kg (1870 lbs.)
ALLOWS ~32% OF MASS TO BE PAYLOAD**

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EARTH ORBITING PLATFORMS

(INCLUDES SPACE STATIONS)

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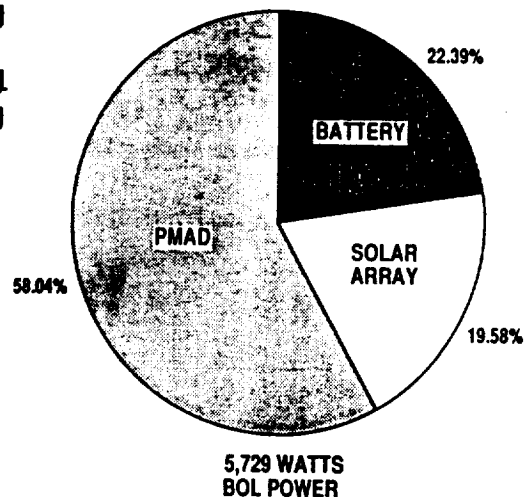
POWER AND THERMAL MANAGEMENT

TDRSS

- NEW TECHNOLOGY ALLOWS 138% MORE POWER FOR THE SAME MASS
- FOR 422.3 kg, NEW TECHNOLOGY GIVES 5729 WATTS

SOLAR ARRAY MASS	82.67 kg
BATTERY MASS	94.53 kg
PMAD MASS	245.08 kg
	422.28 kg

- ADDITIONAL 3319 WATTS OF POWER AVAILABLE WITH NEW TECHNOLOGY FOR THE SAME MASS



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EARTH ORBITING PLATFORMS

(INCLUDES SPACE STATIONS)

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POWER AND THERMAL MANAGEMENT

Milestones:

- 1997 (2) Demo 300 W/sq. m PV concentrator module (>50 W)
- 1997 (2) Ground demo, integrated 2 kW solar dynamic system
- 1996 (2) Demo advanced heat pump designs suitable for micro gravity
- 1996 (2) Demo prototype PMAD brassboard
- 1996 (1) Complete enhanced EPSAT environmental interaction model (LEO, GEO, MEO, POLAR); ground test cryo CPL
- 1996 (1) Demo 300 Wh/kg PV blanket; 100 Wh/kg InP concentrator module
- 1995 (1) Demo 100 Wh/kg boiler plate cells to 1000 cycles (GEO); complete design of cryo CPL for sensors
- 1995 (1) Demo 35% reduction in weight of thermal components
- 1994 (1) Demo G/C shielded electronics box
- 1997 (1) Demo ground test of advanced cryo CPL
- 1997 (1) Demo advanced PMAC integrated avionics system; validate heat pump models
- 1998 (1) Demo 1-2 kg/sq. m thermal management system
- 1998 (2) Flight test heat pumps
- 1998 (2) Complete advanced EPSAT
- 1999 (2) Demo SSF power TD&C facility
- 1999 (1) Demo 100 Wh/kg battery (flightweight)
- 2000 (1) Demo durable high temperature electronics subsystem (200-600 C)
- 2000 (1) Flight test cryo CPL

	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
R&D Resources:	0	0	0	0	0	0	0	0	0	0
Reserves:	0	0	0	0	0	0	0	0	0	0
Total R&D:	0	0	5.1	10.2	13.5	14.3	14.7	14	0	0
C of F (\$M):	0	0	0	0	0.8	1	0.9	0.4	0	

SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS

(INCLUDES SPACE STATIONS)

OAET

POWER AND THERMAL MANAGEMENT

694-11 SPACE PLATFORM TECHNOLOGY - EARTH ORBITING PLATFORMS

	694-11	1993	1994	1995	1996	1997	1998	1999
THERMAL (PV)	-01	0.6	0.8	1.3	1.3	1.4	1.3	
SOLAR DYNAMIC	-02	1.2	3.5	3.6	3.4	3.0	1.9	
PMAD (SD)	-03	0.4	0.8	1.2	1.2	1.2	1.2	
THERMAL (SD)	-04	0.4	0.6	1.0	1.0	1.0	1.0	
PHOTOVOLTAIC	-05	0.6	1.3	1.9	2.3	2.5	3.3	
ENERGY STORAGE	-06	0.7	1.2	1.6	1.6	1.4	1.4	
PMAD (PV)	-07	1.2	2.0	2.9	3.5	4.1	3.9	
TOTALS		5.1	10.2	13.5	14.3	14.7	14.0	

SPACE PLATFORMS TECHNOLOGY PROGRAM

EARTH ORBITING PLATFORMS

(INCLUDES SPACE STATIONS)

OAET

POWER AND THERMAL MANAGEMENT

CONCLUSIONS

- THERE ARE BASE TECHNOLOGIES THAT COULD BE MADE AVAILABLE FOR ORBITING PLATFORMS
 - ADVANCED PHOTOVOLTAIC SOLAR ARRAY (PLANAR AND CONCENTRATOR)
 - IMPROVED BATTERIES (NiH AND SODIUM)
 - SOLAR DYNAMIC SYSTEMS
 - IMPROVED PMAD
 - IMPROVED TMAD
- CODE RP IS CONTINUING TO SUPPORT ADVANCES IN POWER TECHNOLOGIES, INCLUDING:
 - HIGH EFFICIENCY, LIGHT-WEIGHT, RADIATION RESISTANT CELLS
 - ADVANCED CHEMICAL ENERGY STORAGE (NICKEL-HYDROGEN, BIPOLAR NICKEL-HYDROGEN)
 - POWER INTEGRATED CIRCUITS AND FAULT-TOLERANT AUTONOMOUS PMAD
- THESE TECHNOLOGIES CAN BE USED TO ACCOMPLISH SOME COMBINATION OF THE FOLLOWING:
 - REDUCE TOTAL MASS, OR
 - INCREASE PAYLOAD MASS
 - INCREASE POWER AVAILABLE BY UP TO 2x

RC-ITP91.01-71 pm

FOCUSED TECHNOLOGY: EARTH ORBITING PLATFORM POWER AND THERMAL MANAGEMENT SUMMARY

OAET

IMPACT:

- Enable exploitation of earth orbiting space by significant (> 2) improvements in mission critical power and thermal capacities for
 - Wide range of users and missions: Unmanned/manned - Civil, Commercial,
 - Operating requirements: LEO → GEO, EQUATORIAL → POLAR
 - Power levels: 10's W → 10's kW

USER COORDINATION:

- Four element effort: (e.g., presently applied to EOS, ATDRSS, SSF)
 - Determining requirements of planned and proposed missions
 - Assessing impact of upgrade to base technologies
 - Addressing modification and adaptation of technology for mission unique requirements
 - Reviewing with program and project managers

OVERALL TECHNICAL AND PROGRAMMATIC STATUS:

- Basic understanding and development of technology progressing in all areas under base program
- No lack of technology

MAJOR TECHNICAL/PROGRAMMATIC ISSUES:

- Absence of focused effort to bring about:
 - Coordination with broad user and mission base
 - Coordination of multiple disciplines at system level
 - Timely development to level of implementation for flight
- Lack of means to get technology used

RC-ITP91.01-2 pm

THERMAL MANAGEMENT - MILESTONES / SCHEDULE -

- DEMONSTRATE MINI-CAPILLARY PUMPED LOOPS 1994
- DEMONSTRATE 2X-3X SOA FOR CRYOGENIC HEAT PIPES 1995
- DEMONSTRATE 50% WEIGHT REDUCTION FOR THERMAL COMPONENTS 1995
- DEVELOP SEVERAL ADVANCED HEAT PUMP DESIGNS, GOAL OF 3X SOA 1996
- FLIGHT TEST ADVANCED CRYOGENIC HEAT PIPES 1997
- VALIDATE CRYOGENIC HEAT PIPE MODELS 1998
- FLIGHT TEST OF ADVANCED HEAT PUMPS 1998
- VALIDATE HEAT PUMP MODELS 1999

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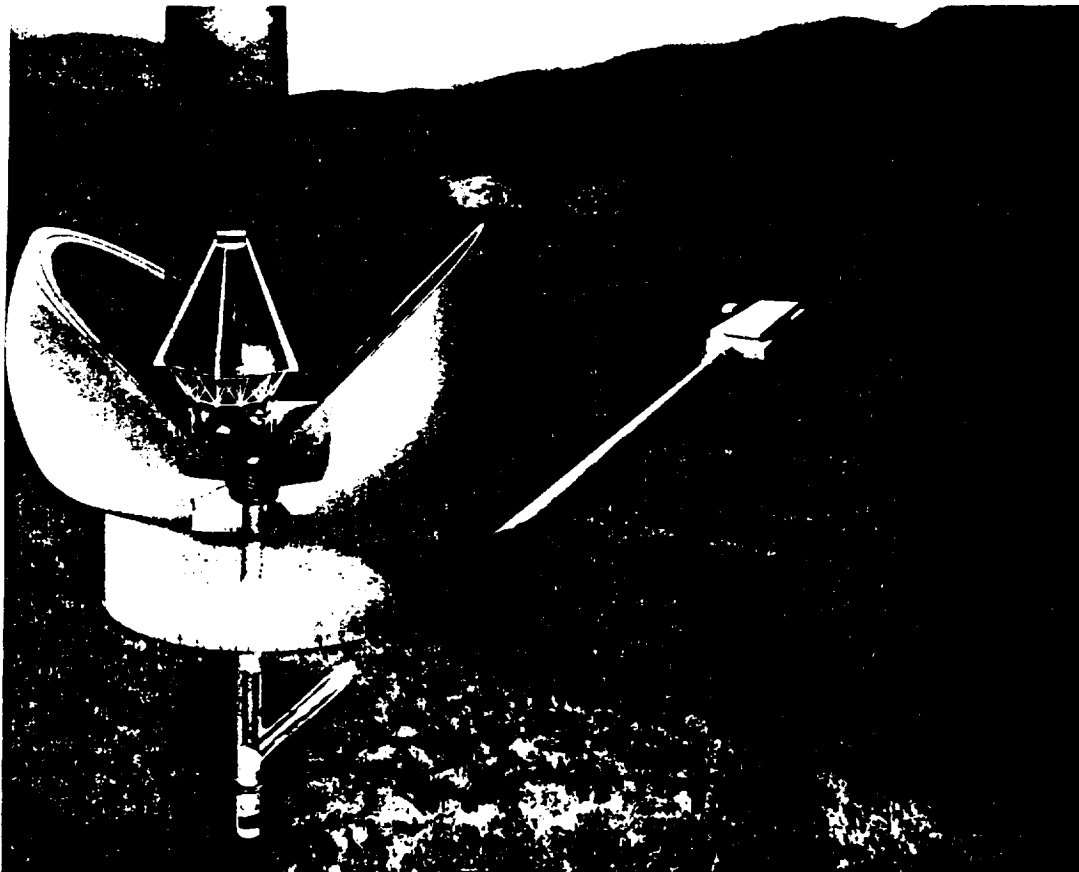
Project SELENE

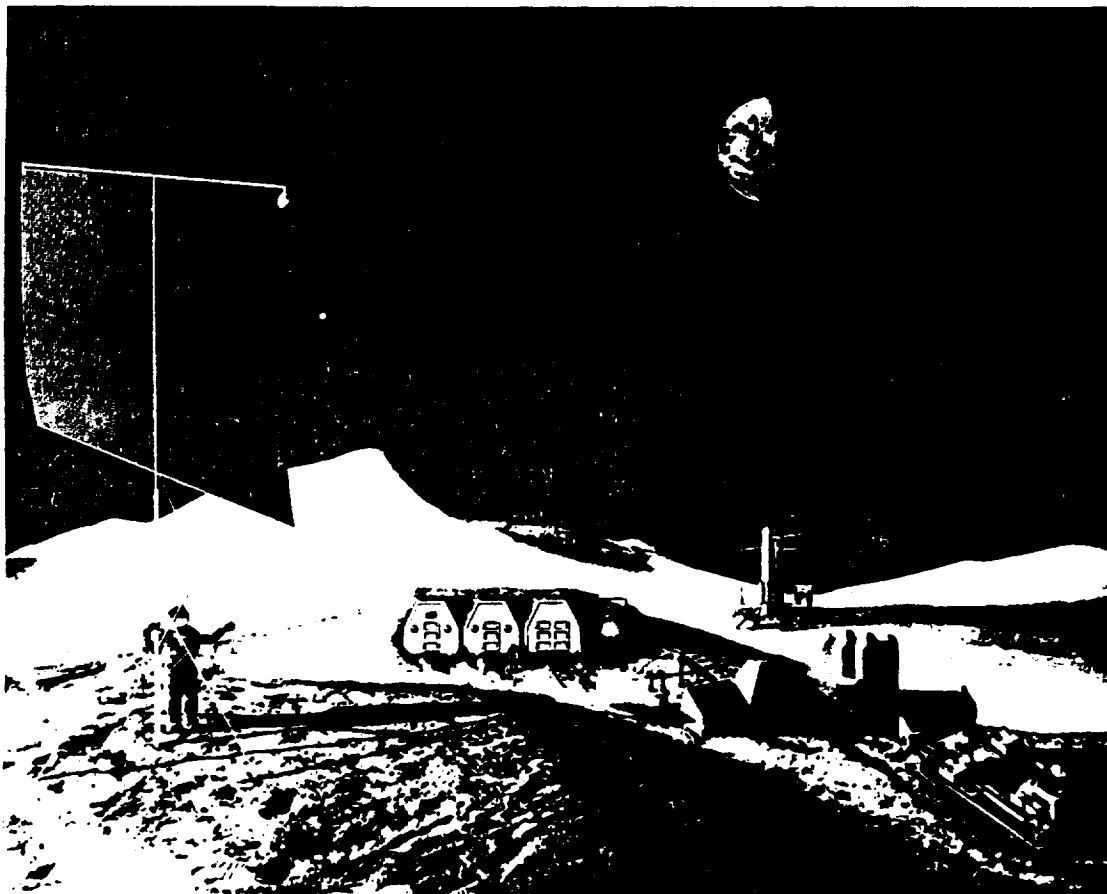
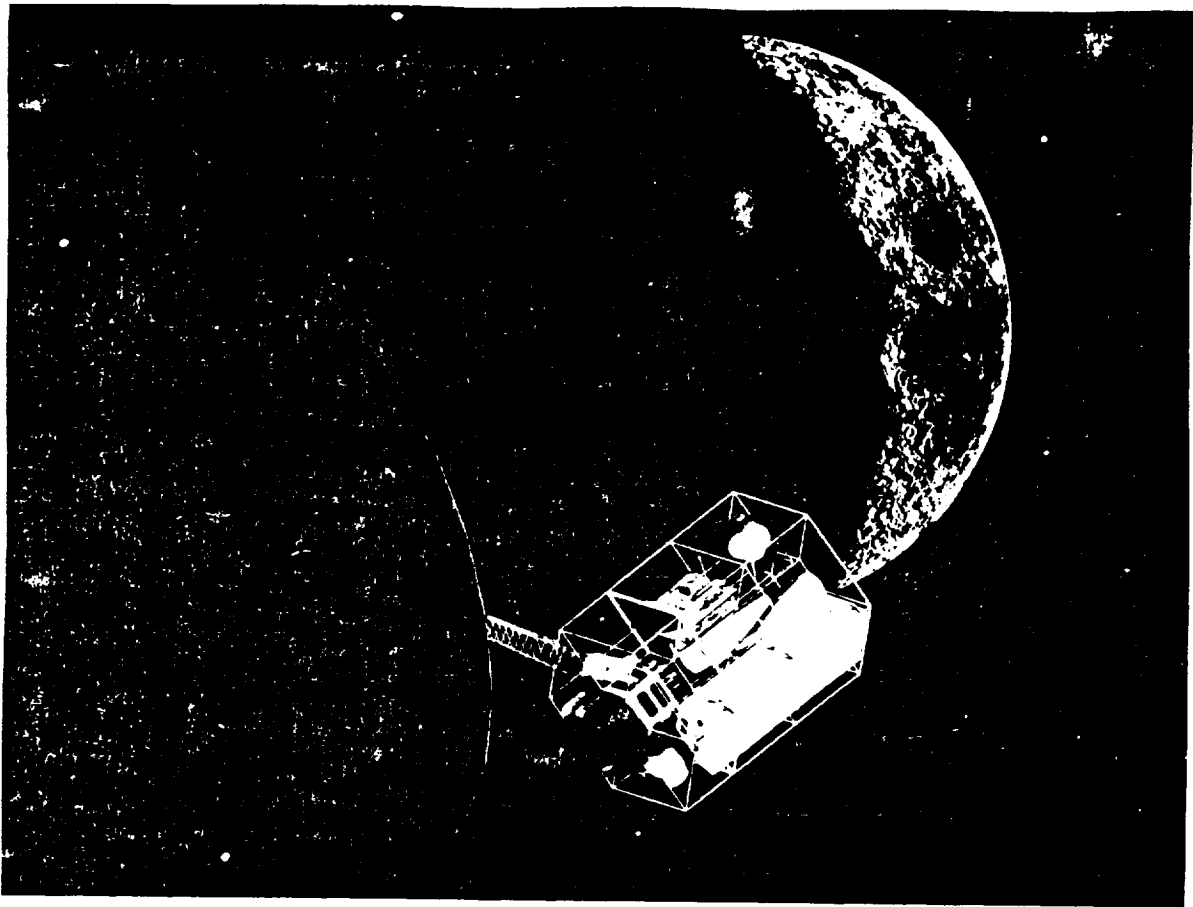
SpaceE Laser Electric ENergy

John D. G. Rather

NASA

"SELENE" is the ancient Greek name for the moon





TRANSPORTATION COSTS WITH MAXIMUM PAYLOADS (1991 \$ PER POUND)

~~OAET~~

VEHICLE	Earth to LEO		Earth to GEO		Earth to Lunar Surface	
	<u>Cost</u>	<u>Max lbs.</u>	<u>Cost</u>	<u>Max lbs.</u>	<u>Cost</u>	<u>Max lbs.</u>
Shuttle	\$6,700	45,000	72,700	5,000*	50,000	10,000
Titan	\$5,300	38,000	30,000	10,000	39,000	10,000
Shuttle Derived Vehicle	\$3,400	89,000	25,000	10,000	34,000	10,000
National Launch Systems (NLS)	\$3,000	50,000	22,700	10,000	34,000	10,000
	\$1,200	150,000	13,600	10,000	25,000	10,000

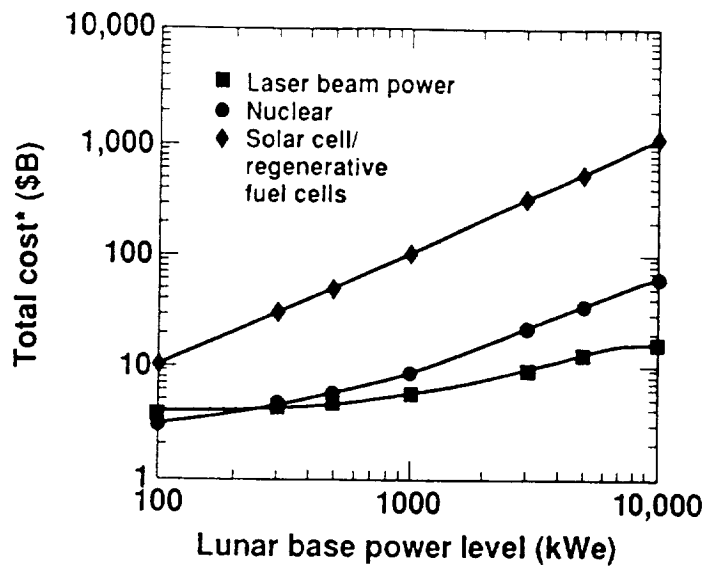
*Use of IUS with 500lb payload results in high \$/lb relative to other options which assume a new upper stage with 10,000lb payload.

91-2251

High-Power Space Applications

- Electric propulsion for economical orbit raising (LEO to GEO, LEO to LLO, etc.)
- Power for lunar base
- Life support for large, manned space stations
- Industrial processes
- K-Band traffic monitoring and identification
 - Air traffic monitoring and identification
 - Ship traffic monitoring and identification
 - Clear air turbulence mapping
 - Defense
- Direct-broadcast TV transmission
- Advanced remote sensing

Comparison of costs of candidate lunar surface power architectures



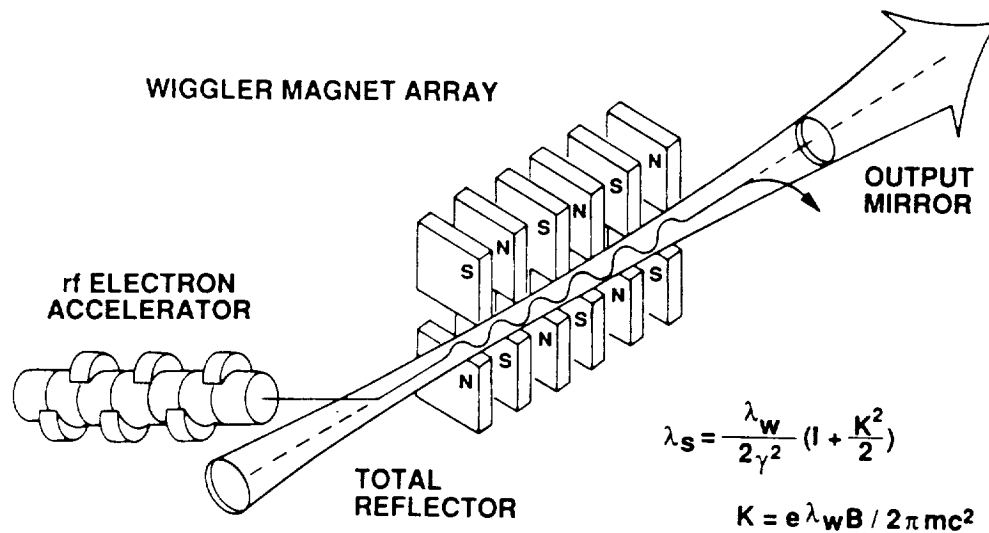
* Costs include estimated transportation costs in 1990 dollars

Refs:

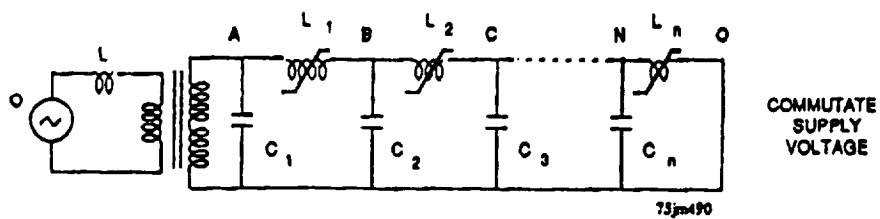
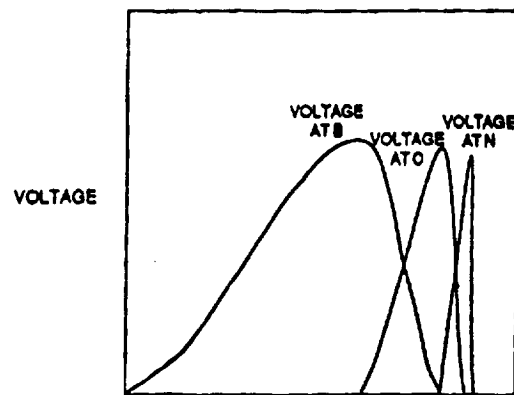
- (1) – NASA Lewis Research Center
- (2) – NASA Pathfinder Program Plan

- **New optical technologies:
The Key to implementation**

BASIC ELEMENTS OF A COMPTON - REGIME FREE ELECTRON LASER

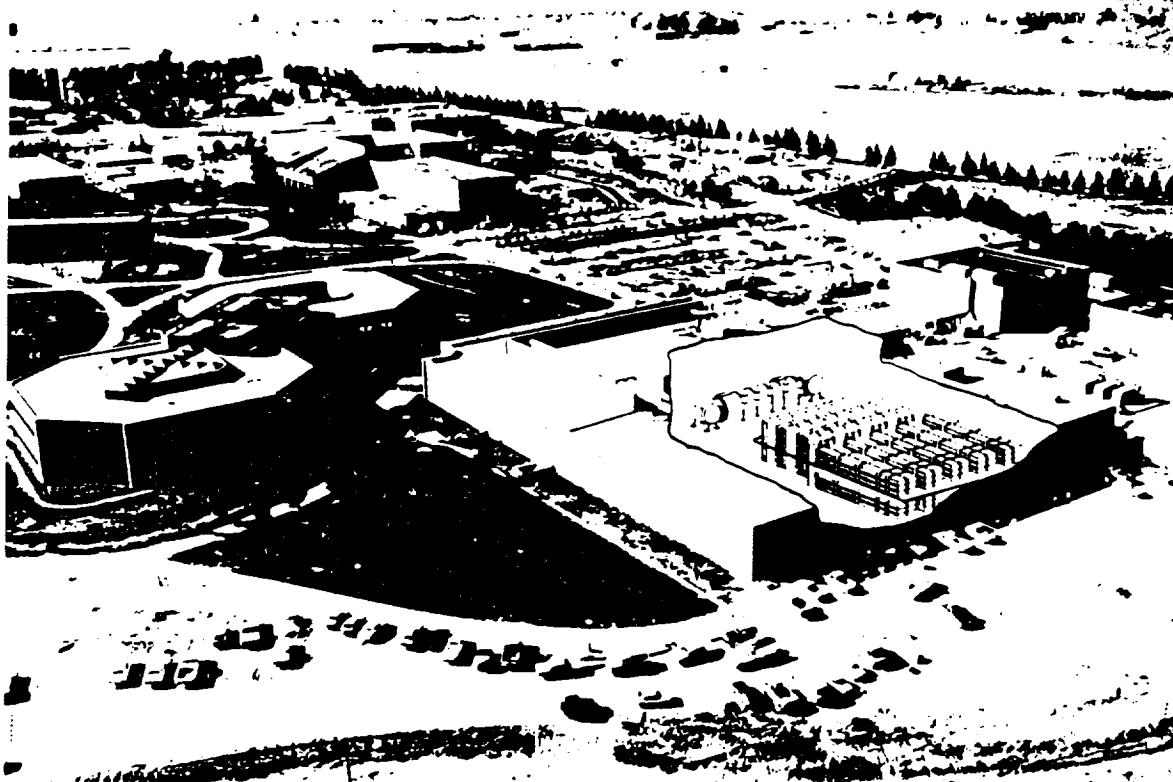


TYPICAL MAGNETIC SWITCH OPERATION

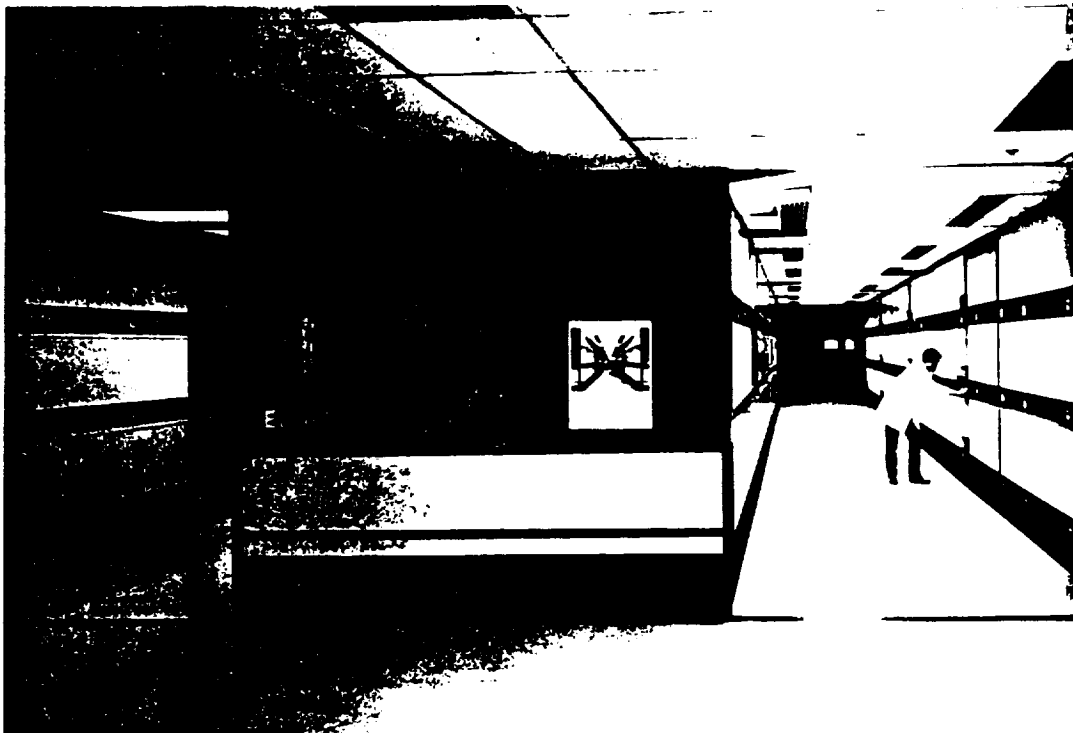


REFERENCE: SCIENCE RESEARCH LABORATORY

AVLIS Full-Scale Demonstration Facility

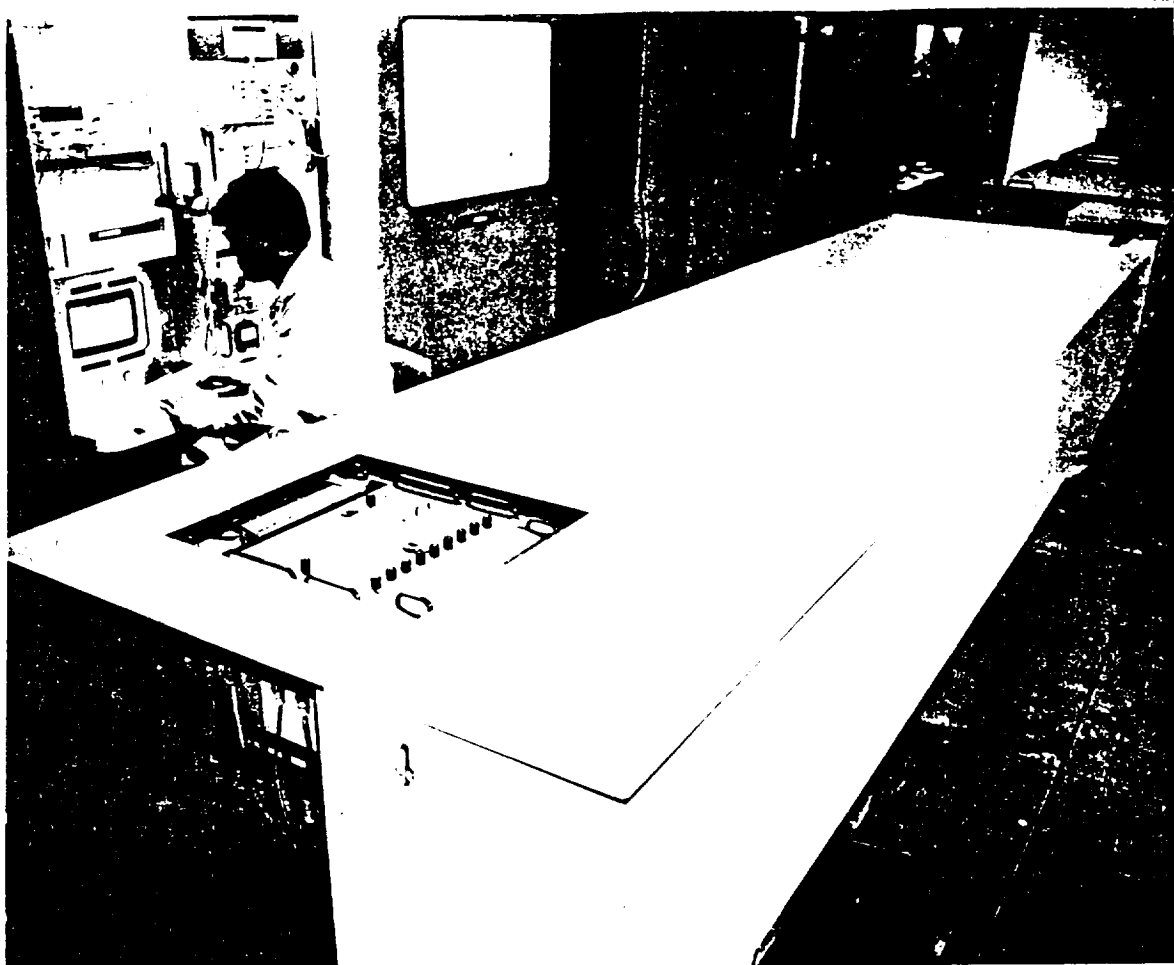


Copper laser corridors provide more than 8 kW of average power in around-the-clock operations

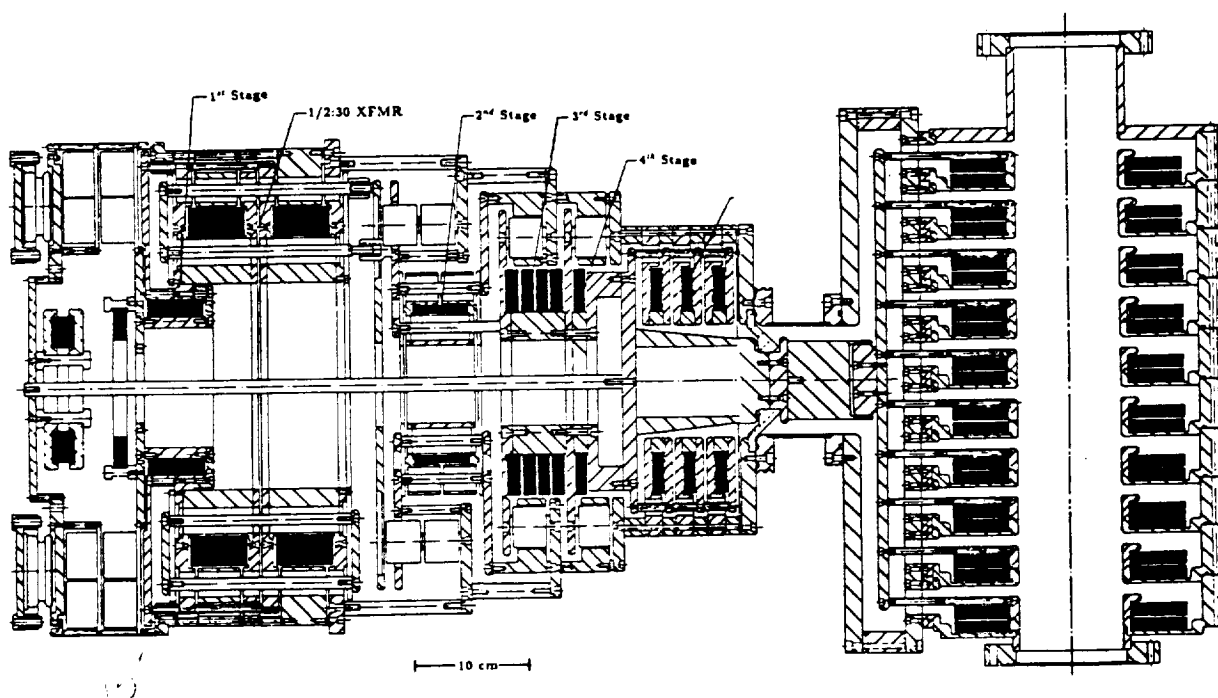


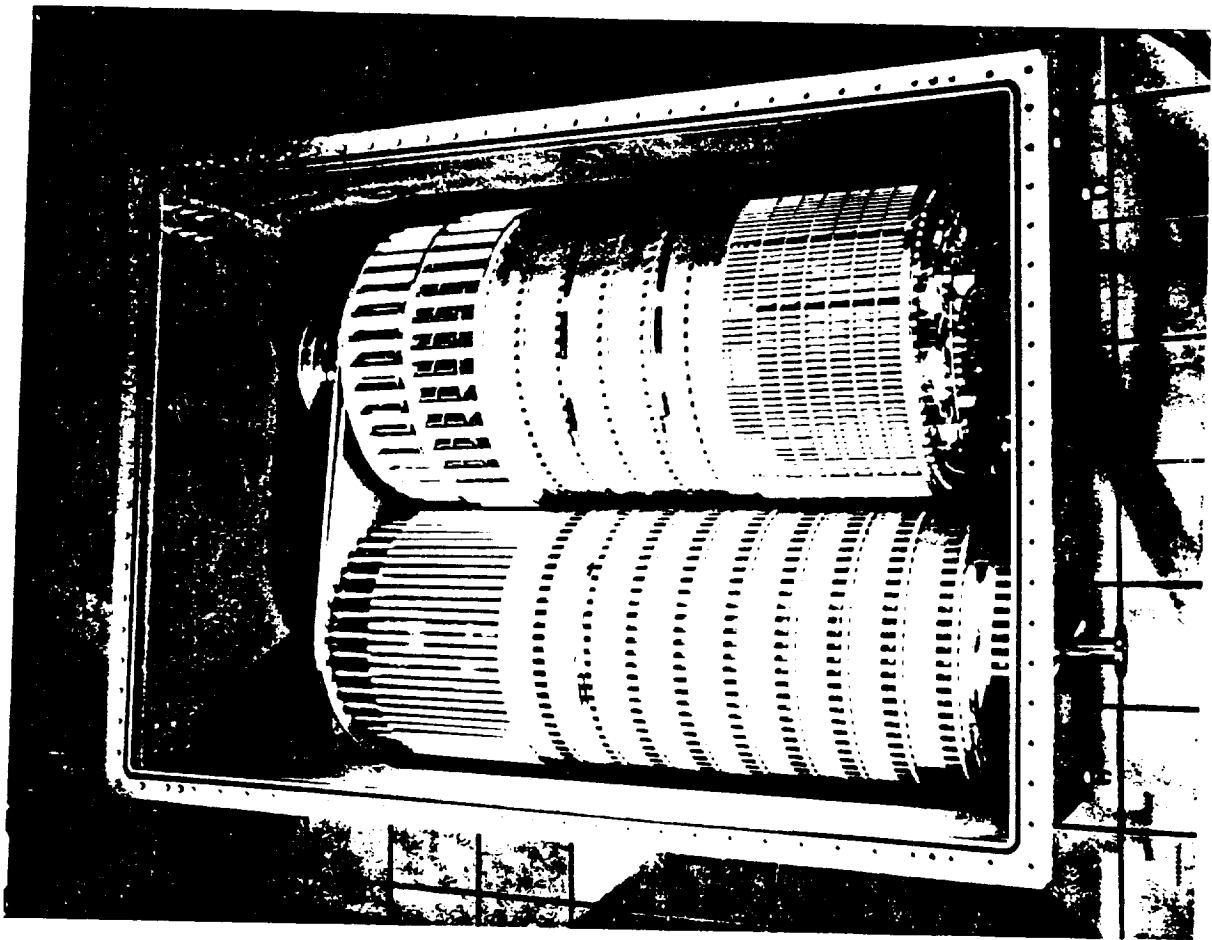
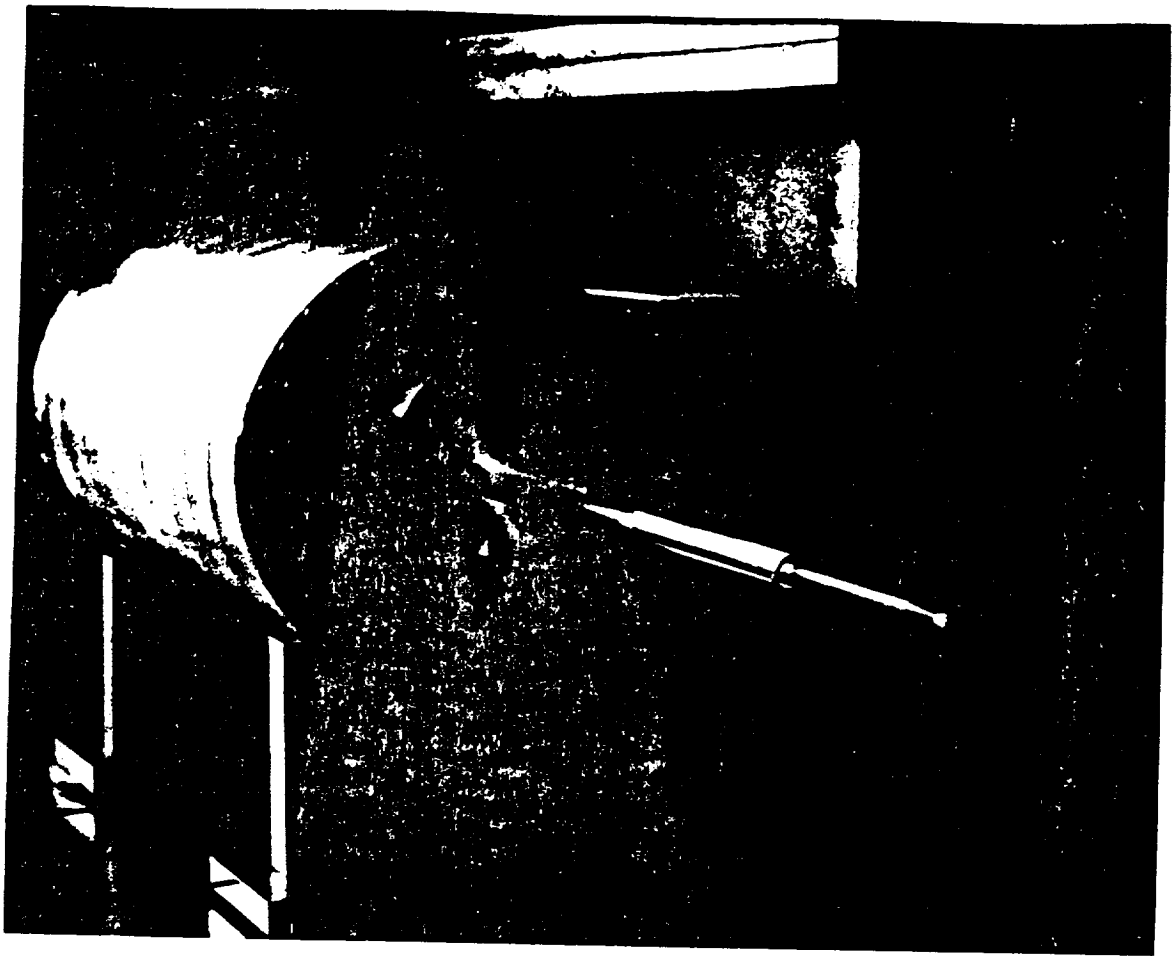
1.0 0590.1506
24 RSH

11/90

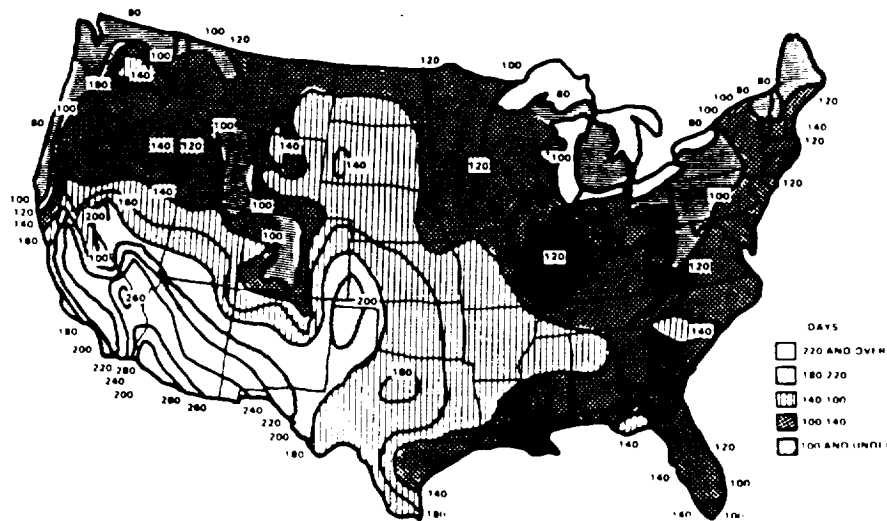


**SNOMAD-V NONLINEAR MAGNETIC COMPRESSOR AND
1 MeV HIGH GRADIENT ACCELERATOR SECTION**



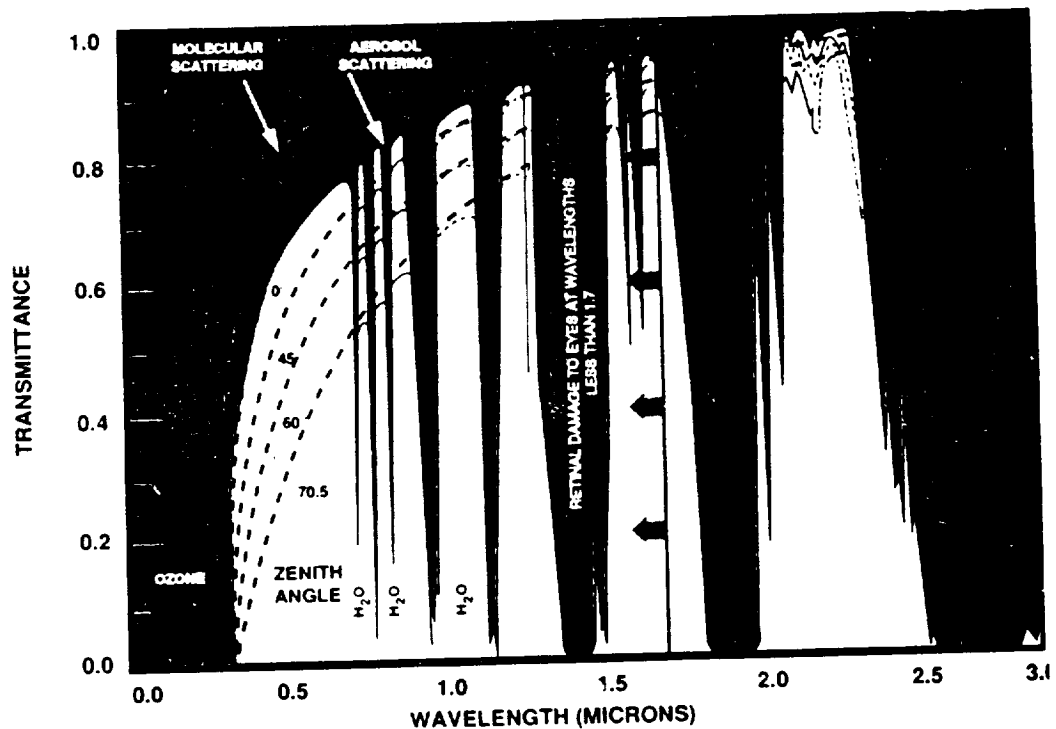


**(U) LOCATION OF GROUND SITES DEPENDS
PRIMARILY UPON AVERAGE ANNUAL NUMBER
OF CLEAR DAYS**

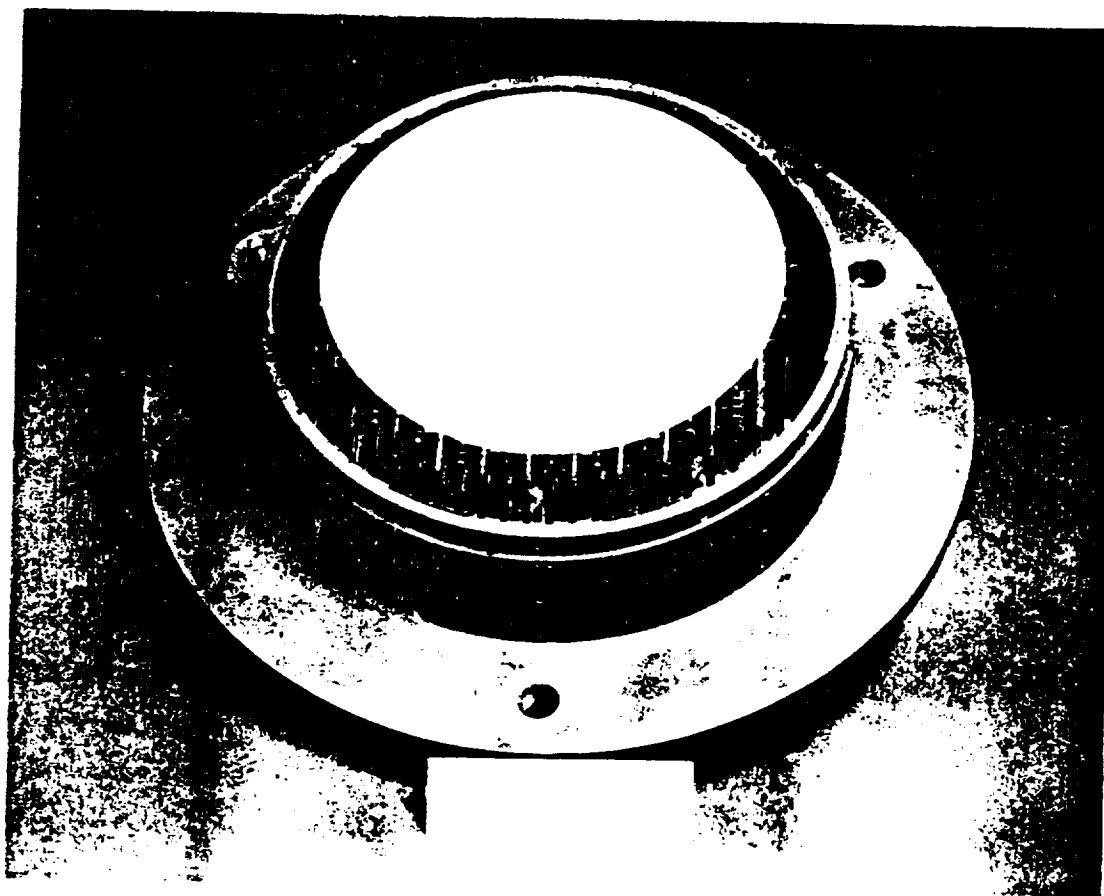
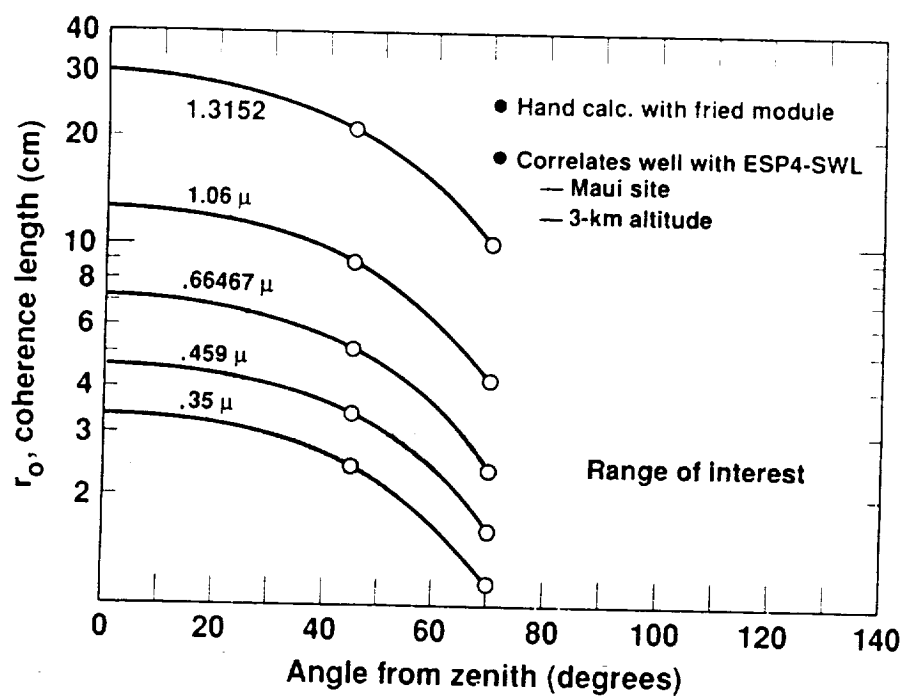


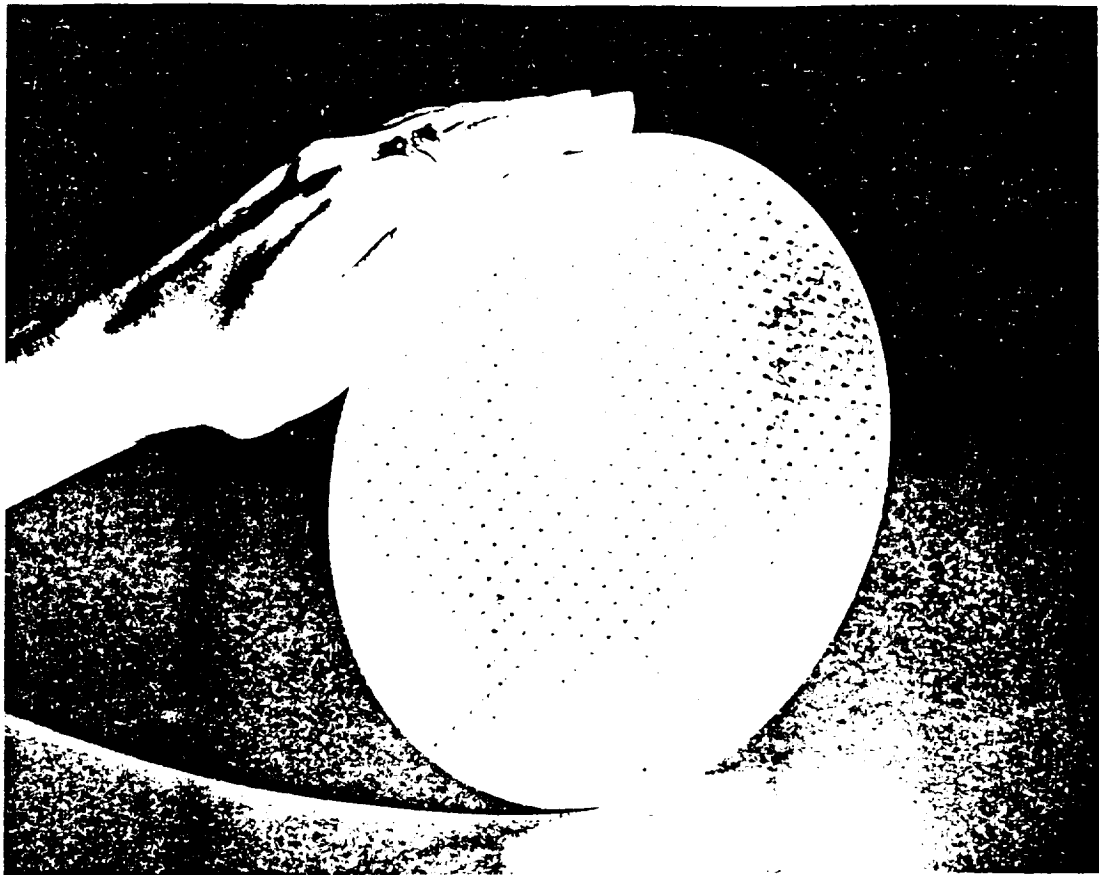
ATMOSPHERIC TRANSMITTANCE TO SPACE

LASERS LOCATED AT 2KM ELEVATION ABOVE SEA LEVEL

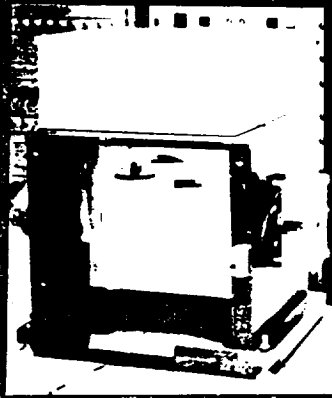


Turbulence coherence length as a function of wavelength and zenith angle



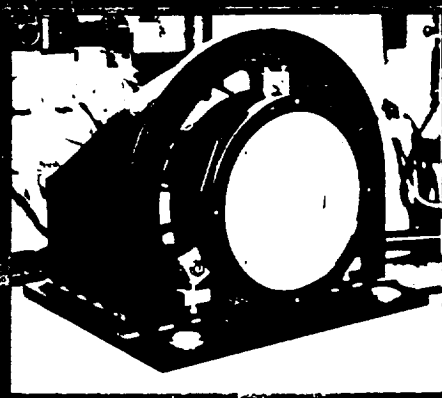


COOLED DEFORMABLE MIRRORS



UTOS HICLAS

ACTUATORS: 69
STROKE: 30 μm
ACTIVE AREA: 16 cm DIAMETER
SURFACE FIGURE: $\sim 0.1 \lambda_{\text{rms}} (\lambda = 0.633 \mu\text{m})$



ITEK LCDM

ACTUATORS: 241 (+ Two Guard Bands)
STROKE: 4 μm
ACTIVE AREA: 16 cm DIAMETER
SURFACE FIGURE: $\sim 0.02 \lambda_{\text{rms}} (\lambda = 0.633 \mu\text{m})$

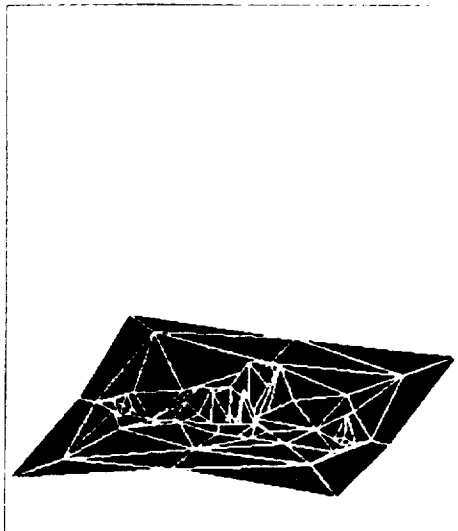


137900-2

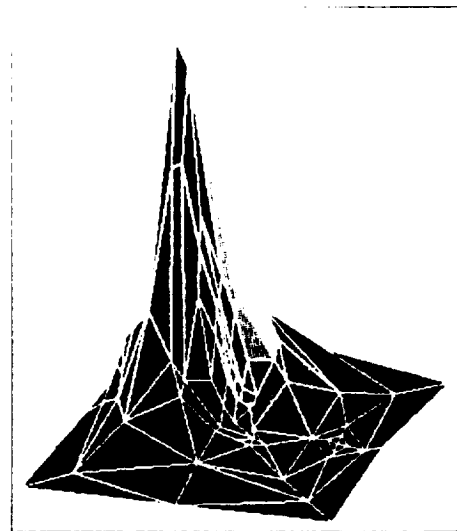
LACE Data 30 November 1990

SMC 182, Samples 180-184

SMC 181, Samples 160-164

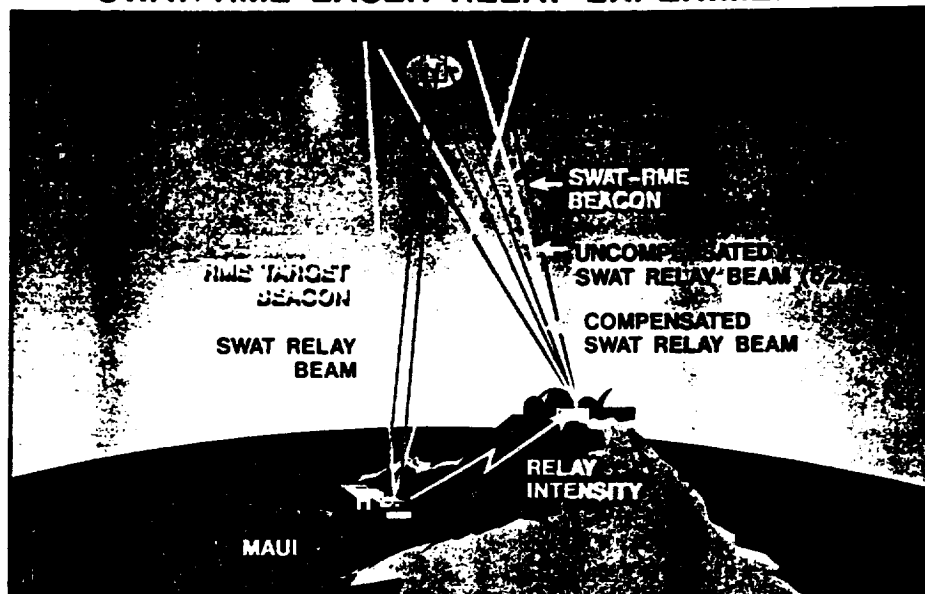


Uncompensated



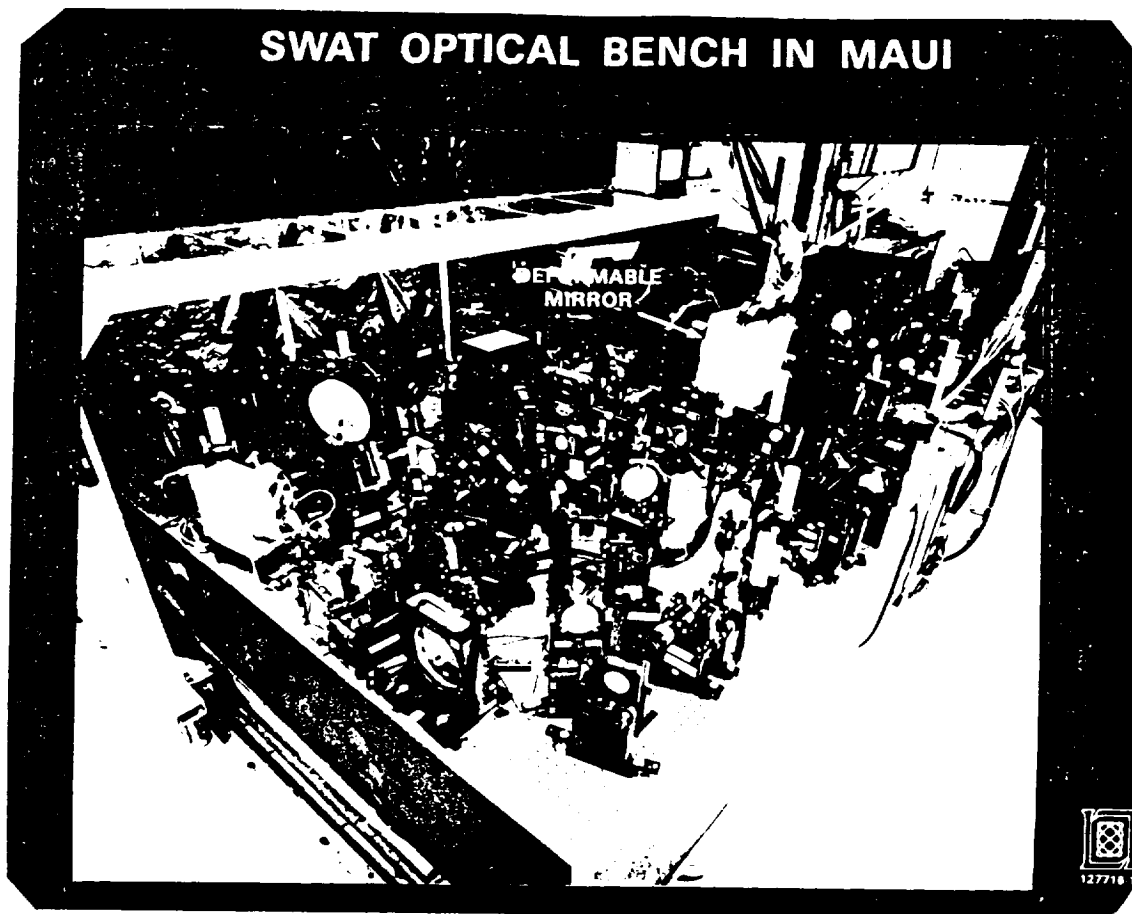
Compensated

SWAT/RME LASER RELAY EXPERIMENT



139167-1

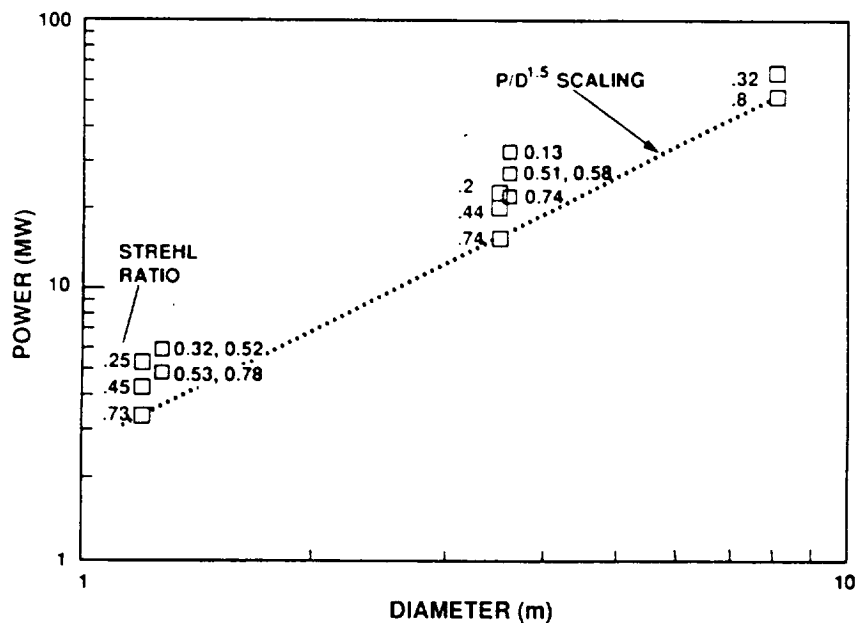
SWAT OPTICAL BENCH IN MAUI

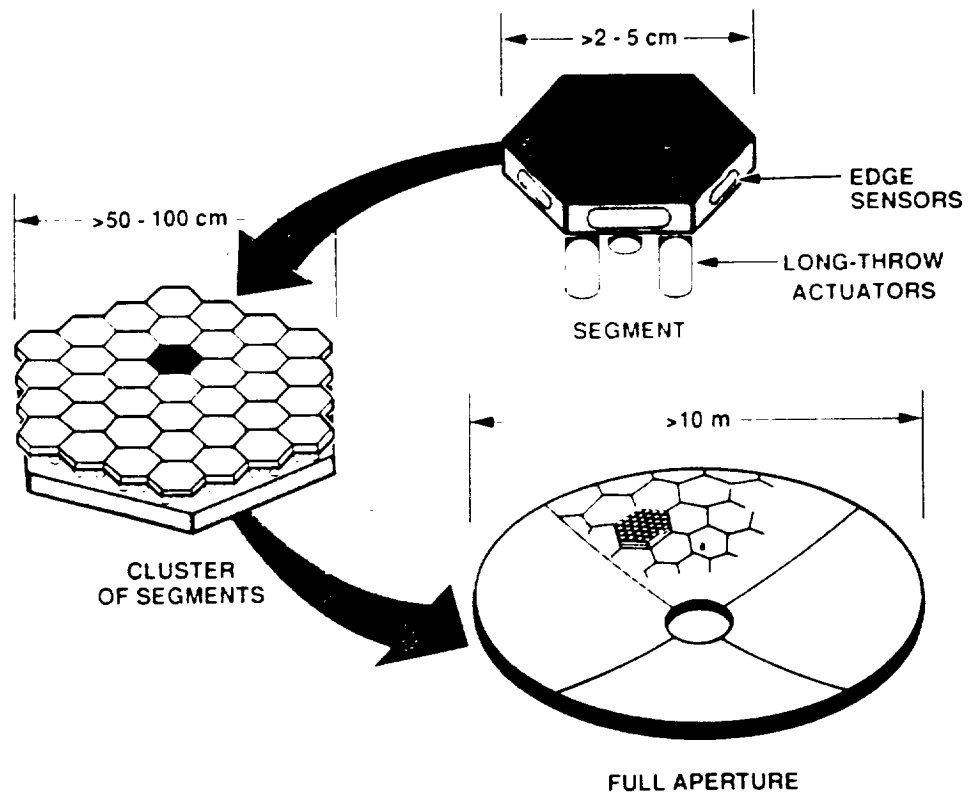
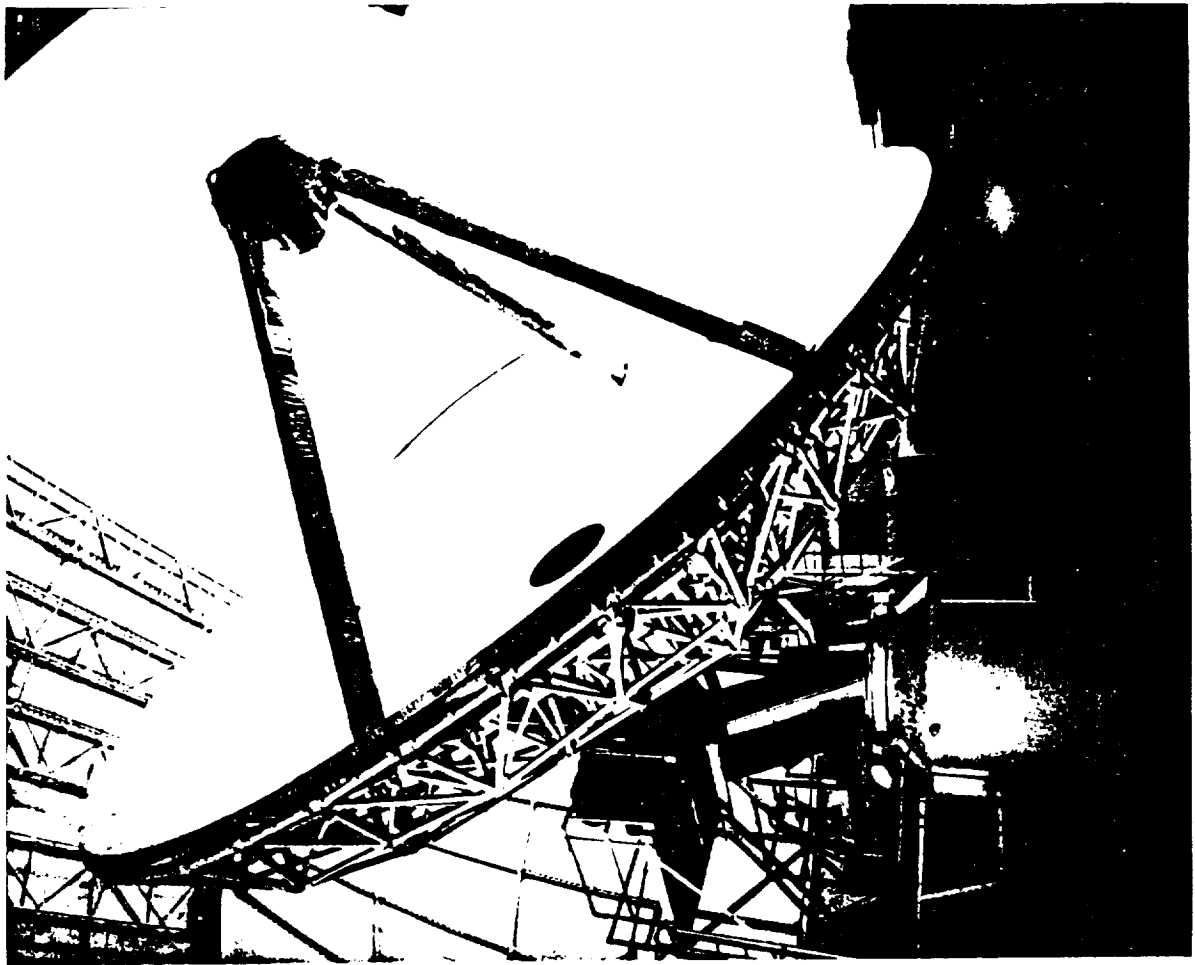


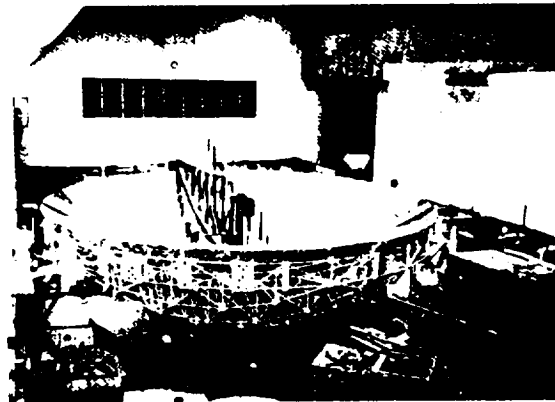
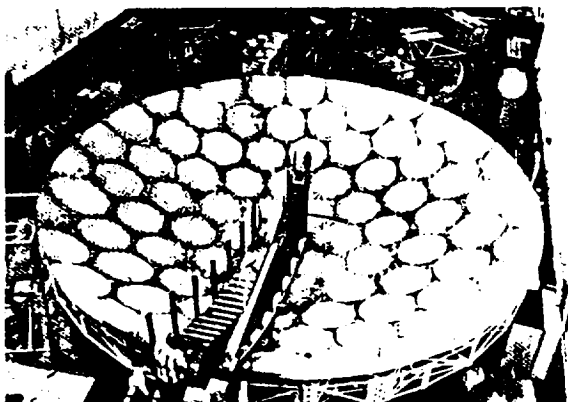
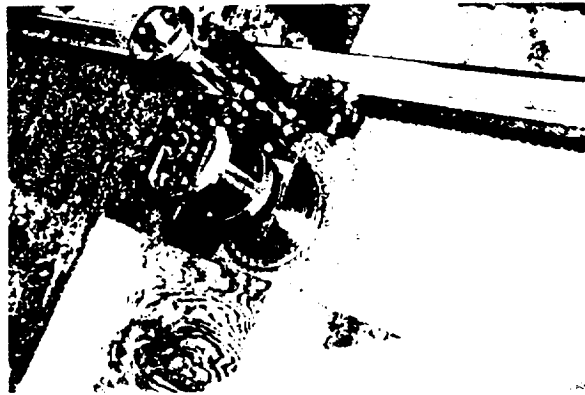
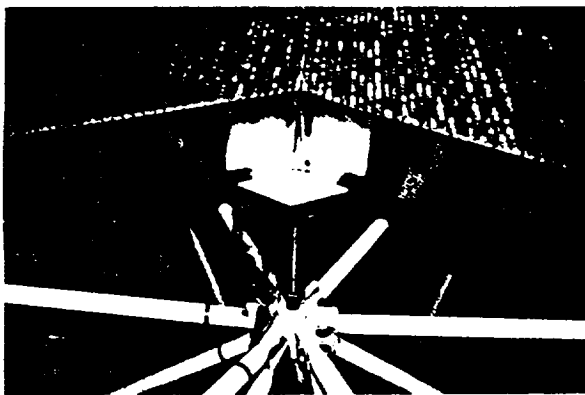
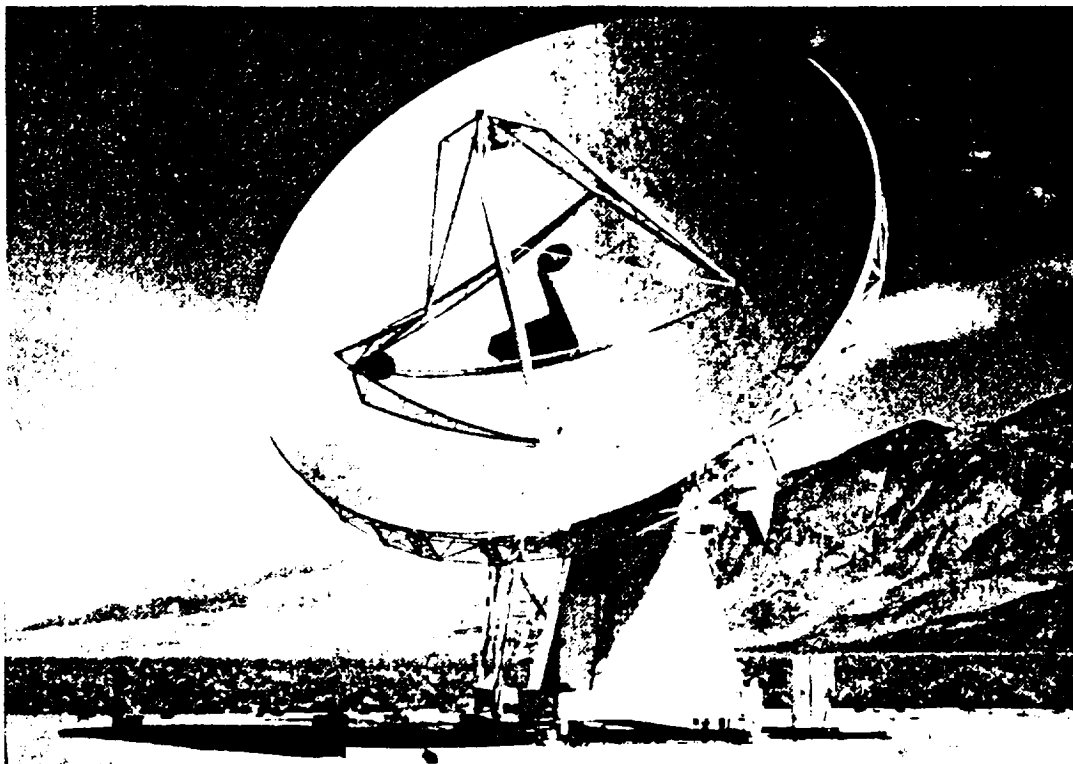
BASELINE RESULTS

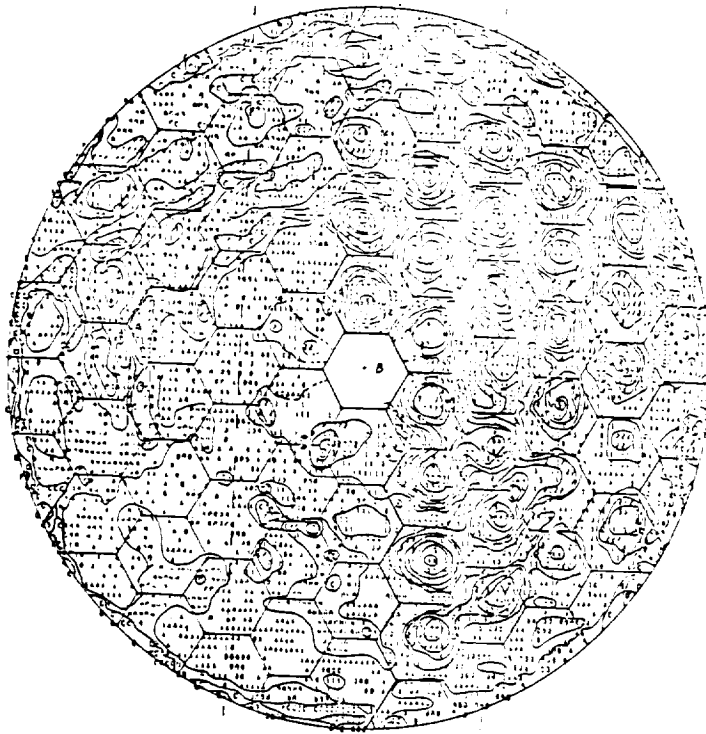
STREHL RATIOS FOR
VARIOUS POWERS AND DIAMETERS

WITH TWO REALIZATIONS OF KOLMOGOROV FLUCTUATIONS





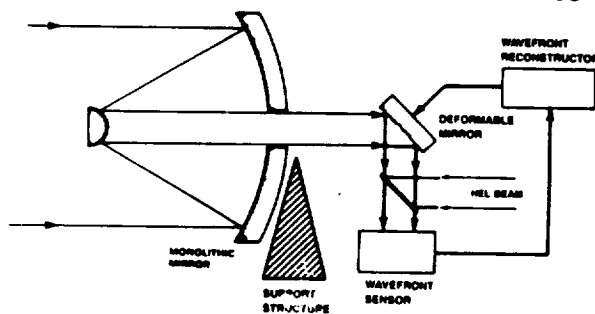




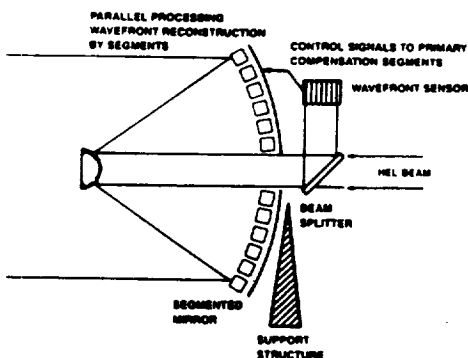
Computer map of prototype dish surface as measured following the initial remounting of the panels. Approximate boundaries of the panels are drawn in, and approximate, hand-drawn contours are shown. Positive heights above a best-fit paraboloid are indicated by the digits 0-9, negative heights by the letters A-I, in 25 μ m (0.001 inch) steps. If a given point does not fall within $\pm 1/4$ unit of an integer value, a blank is printed. The panels to the left of the heavy jagged line had "stretchers" attached and those to the right did not (see text). Note the obvious "crowning" of the unstretched panels as compared with the stretched ones. The rms surface errors for the two areas are 10 μ m and 60 μ m respectively, and the mean value is 50 μ m.

PAMELA — A Lower Cost Approach

CONVENTIONAL TELESCOPE WITH ADAPTIVE OPTICS



PAMELA

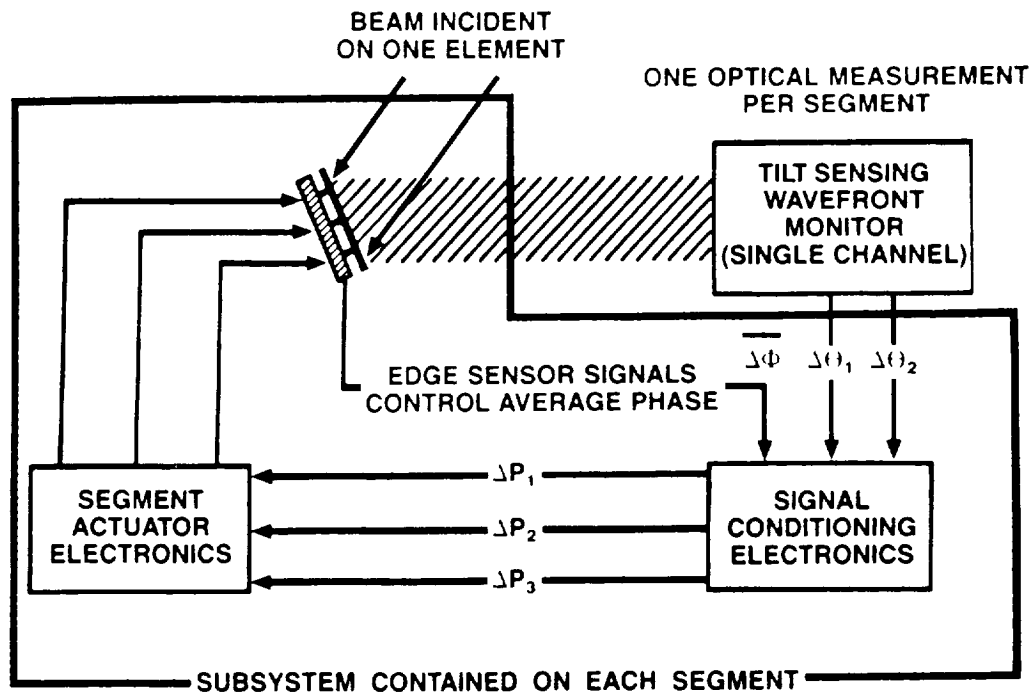


	CONVENTIONAL ADAPTIVE OPTICS	PAMELA
PRIMARY	<input checked="" type="radio"/> MONOLITHIC OR LARGE SEGMENTS	<input type="radio"/> MASS PRODUCED SEGMENTS
SECONDARY	<input checked="" type="radio"/>	<input type="radio"/>
SUPPORT STRUCTURE	<input checked="" type="radio"/>	<input type="radio"/>
WAVEFRONT SENSOR	<input checked="" type="radio"/>	<input type="radio"/>
WAVEFRONT RECONSTRUCTOR	<input checked="" type="radio"/>	<input type="radio"/> NOT REQUIRED
CONTROL PROCESSOR	<input checked="" type="radio"/> MULTI CHANNEL	<input type="radio"/> ON ARRAY + 6 ROW OR SEGMENT
COMPENSATION MIRROR	<input checked="" type="radio"/> HIGH DENSITY MEMBRANE OR SEGMENTS	<input type="radio"/> ACTUATORS ONLY

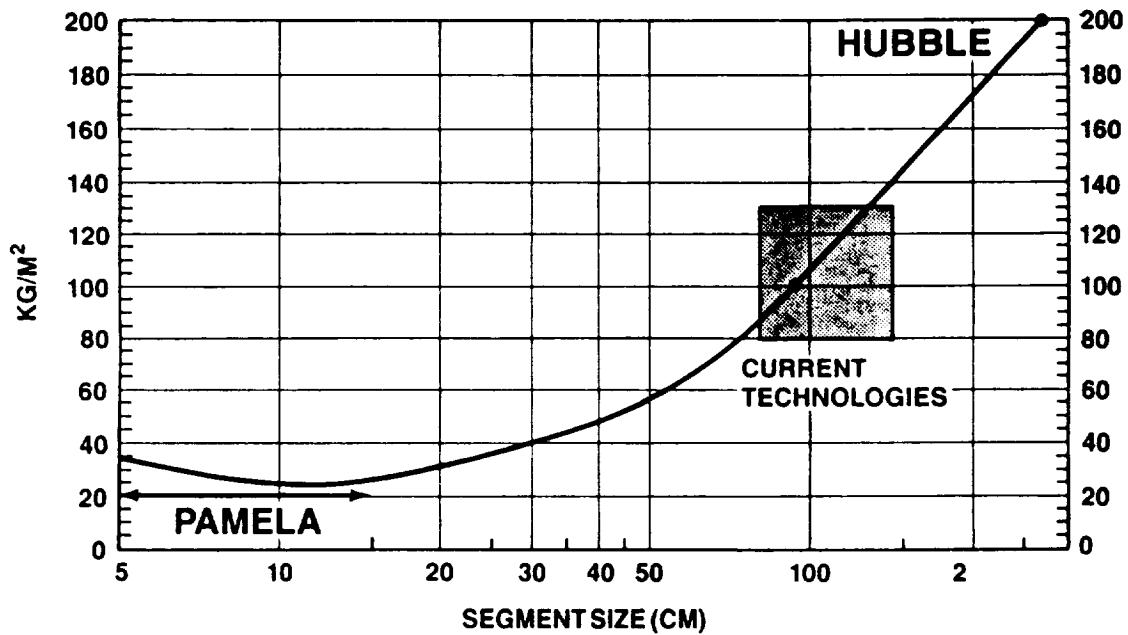
☒ HIGH COST

☐ LOW COST

TTPM FUNCTIONAL BLOCK DIAGRAM



MIRROR AREAL MASS DENSITIES AS A FUNCTION OF SEGMENT SIZE



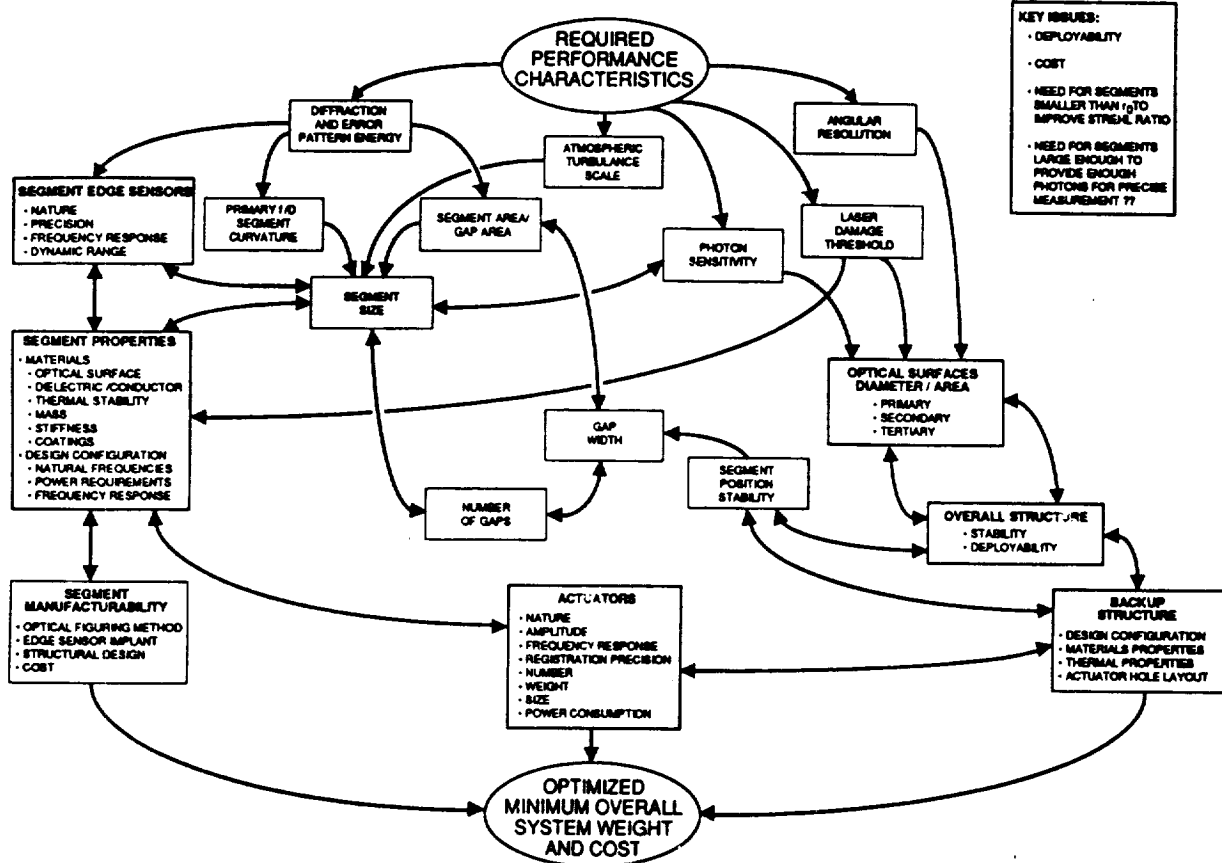
ORIGINAL PRINTED
OF POOR QUALITY

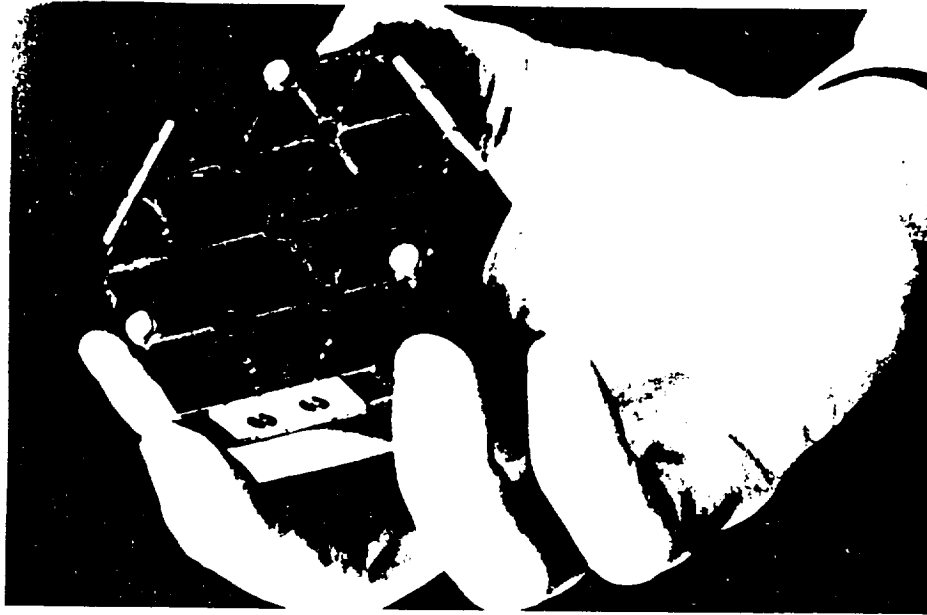
CONSTRAINTS AFFECTING SEGMENT SIZE

WHAT DETERMINES THE PHASED ARRAY ELEMENT SIZE ?

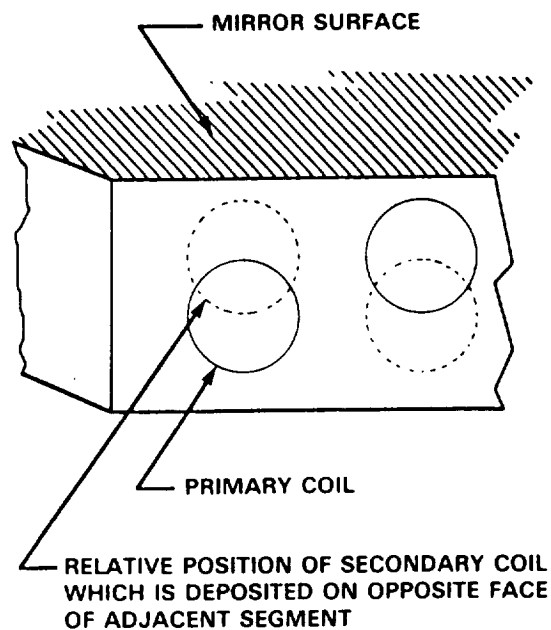
- UPPER LIMIT
 - SCALE SIZE OF OPTICAL DISTURBANCES
 - VIBRATION-INDUCED DISTURBANCES
 - ATMOSPHERIC DISTURBANCE SCALE
 - THERMAL INERTIA
- LOWER LIMIT
 - SEGMENT FABRICATION COSTS
 - ACTUATOR STROKE
 - SYSTEM WEIGHT
 - SYSTEM COMPLEXITY

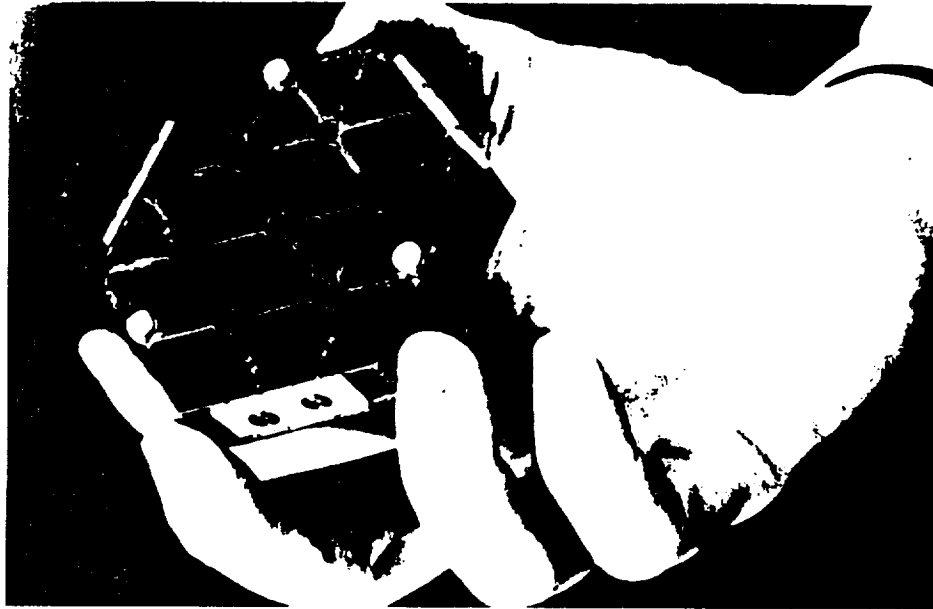
SEGMENT DESIGN ISSUES



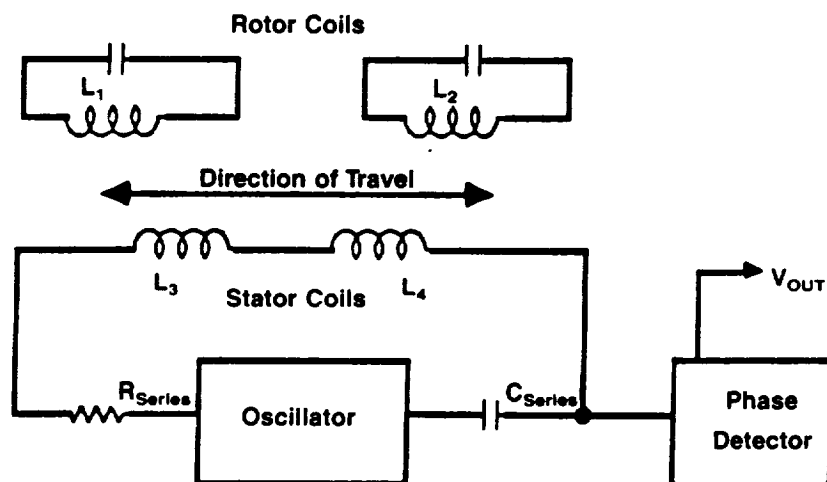


ARRANGEMENT OF SENSING COILS ON SEGMENT EDGE

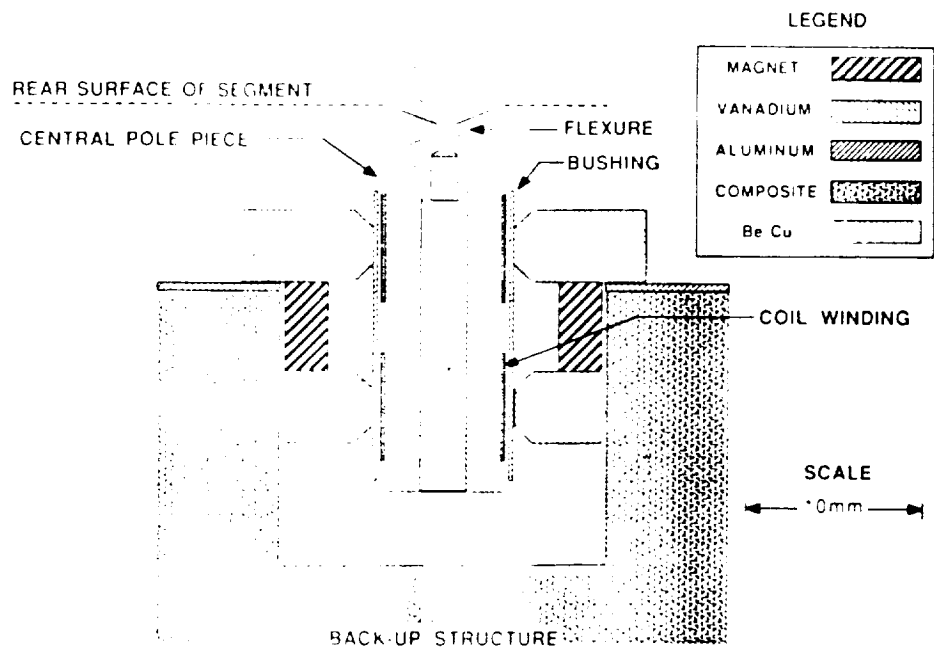




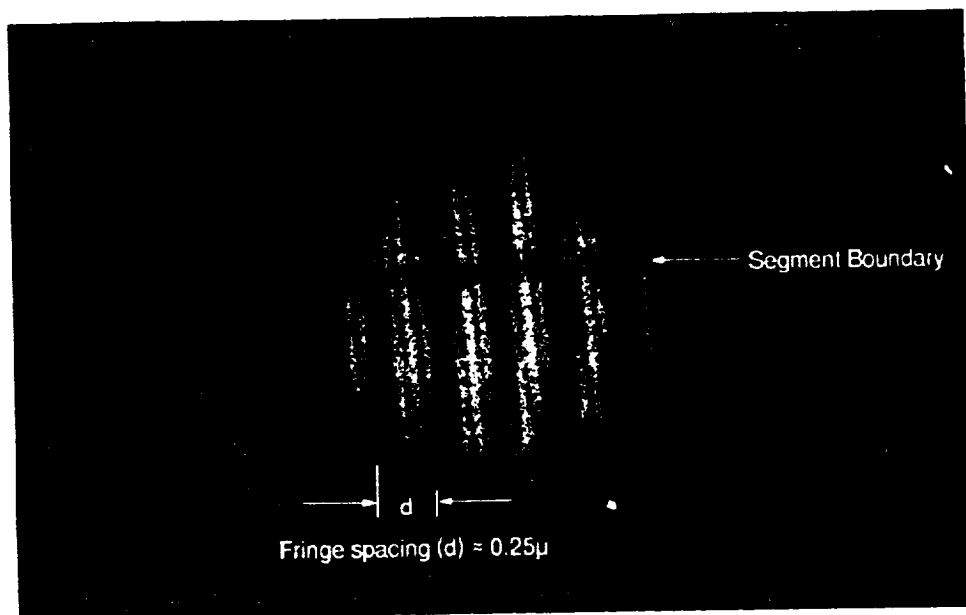
Edge-Matching Sensor Circuit Diagram



ACTUATOR DETAIL



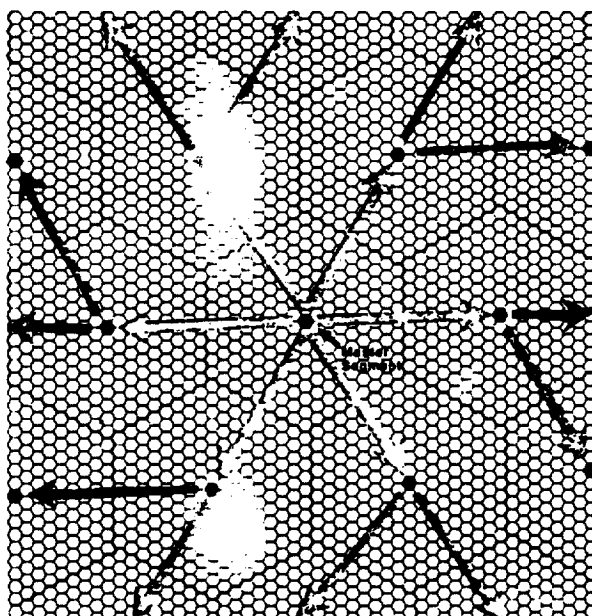
WHITE LIGHT FRINGES



STEPS IN RAPID CONVERGENCE ALGORITHM

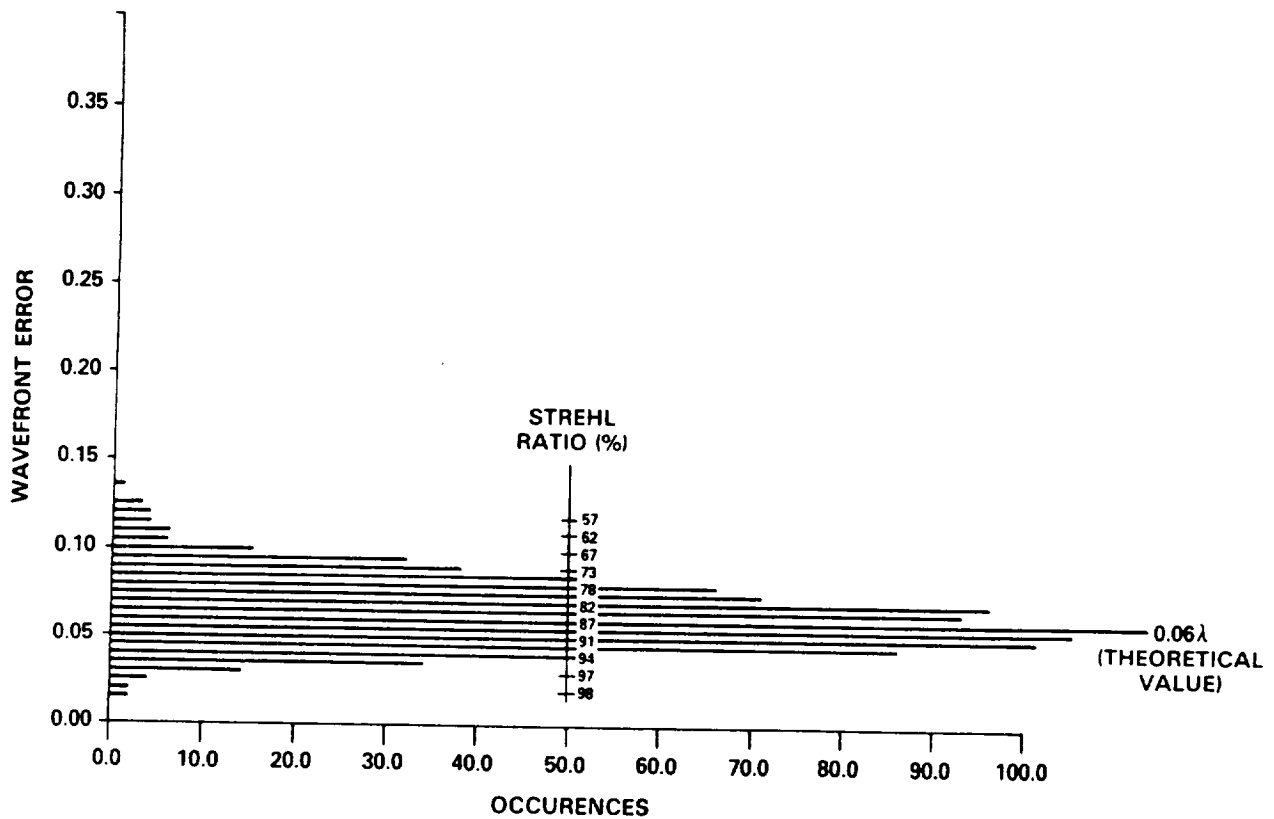
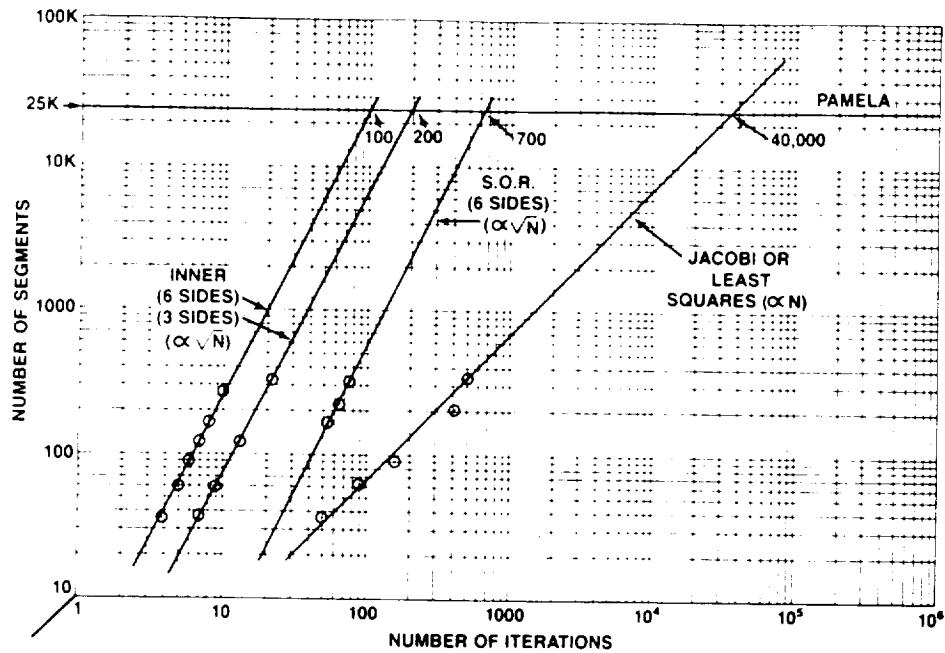
- EDGE MATCH ALL SEGMENTS
- MEASURE TILTS OF ALL SEGMENTS
- APPLY AND FIX SEGMENT TILTS WHILE EDGE MATCHING
- COMPUTE PISTONS OF ALL REFERENCE SEGMENTS AT CENTER OF EACH CLUSTER BY INTEGRATING TILTS ALONG SPECIFIED PATHWAYS (RELATIVE TO MASTER SEGMENT)
- ADJUST AND FIX PISTONS OF REFERENCE SEGMENTS AT CENTER OF EACH CLUSTER
- PISTONS OF REMAINING SEGMENTS WITHIN EACH CLUSTER ARE ADJUSTED BY EDGE MATCHING TO REFERENCE SEGMENT

- REFERENCE SEGMENTS
- DEFINES CLUSTERS
- POSSIBLE PATHWAYS OF PISTON COMPUTATION



SURFACE SETTING ALGORITHMS

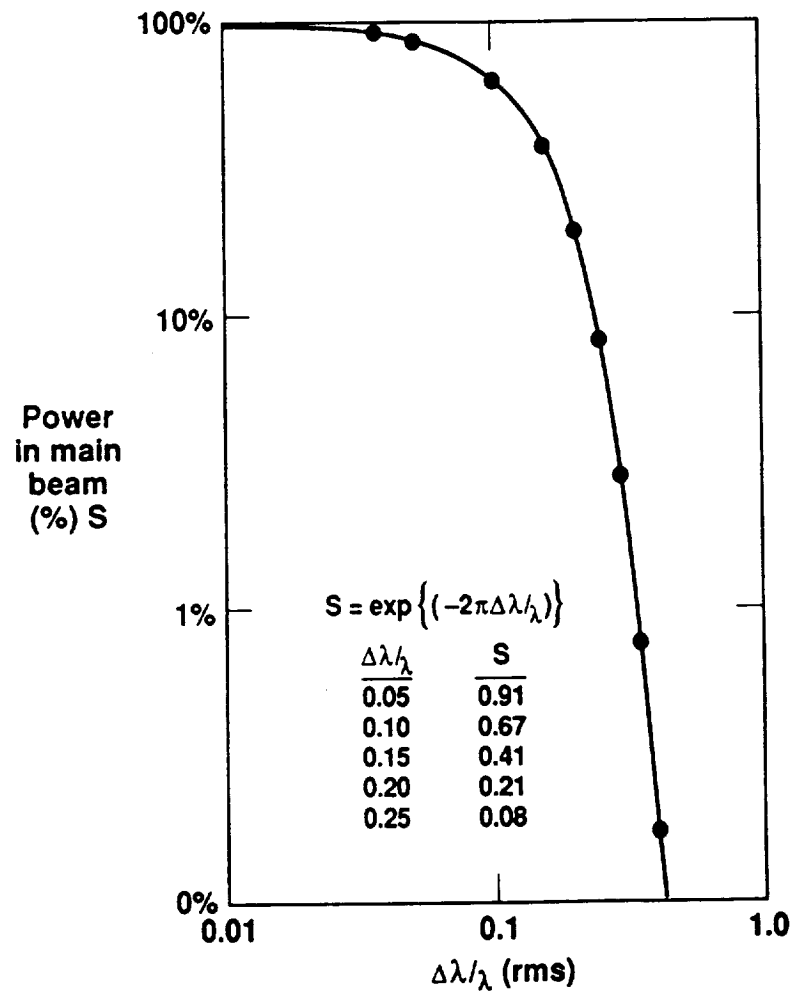
STEP FUNCTION RESPONSE (CONVERGENCE TIME)

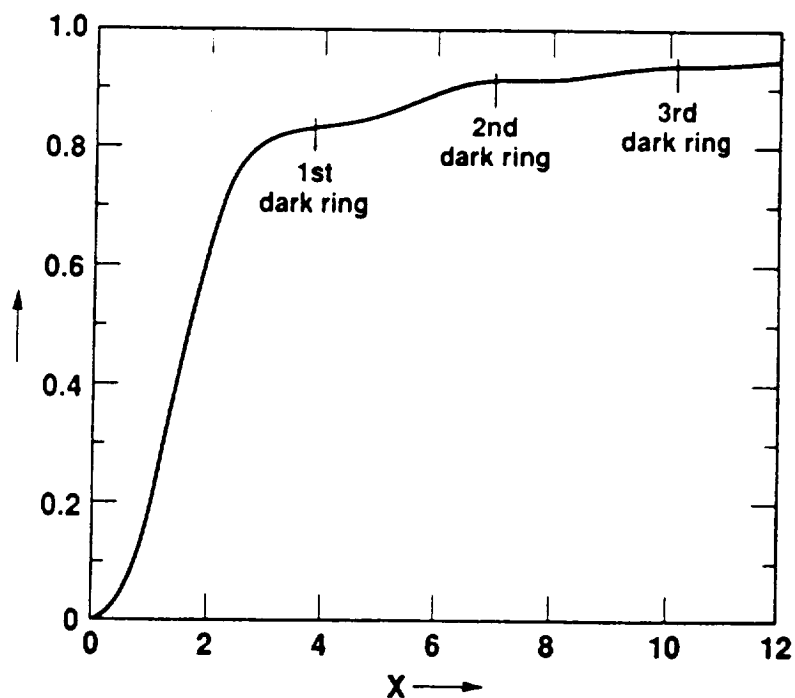
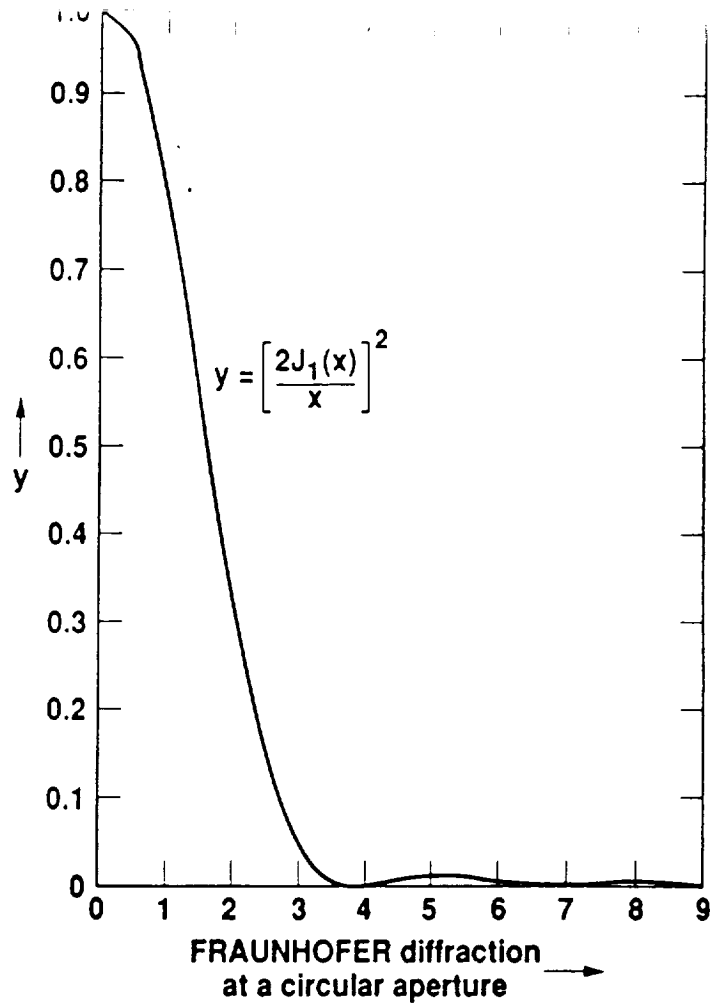


The integrated control concept is scalable

- Simple sensor arrays
 - CCDs
 - Quad cell witness plate
- Linear distribution of sensor data to segments
- "Smart" self-processing segments
- Long stroke actuators
- Only parallel processing required

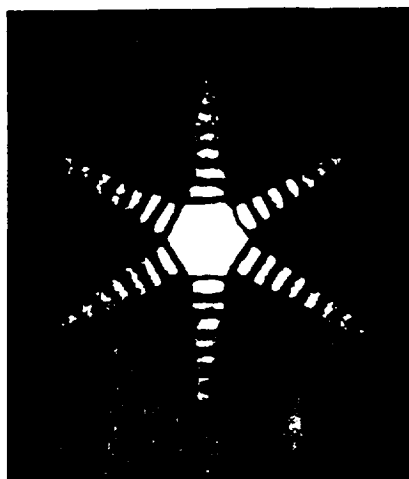
Strehl ratio



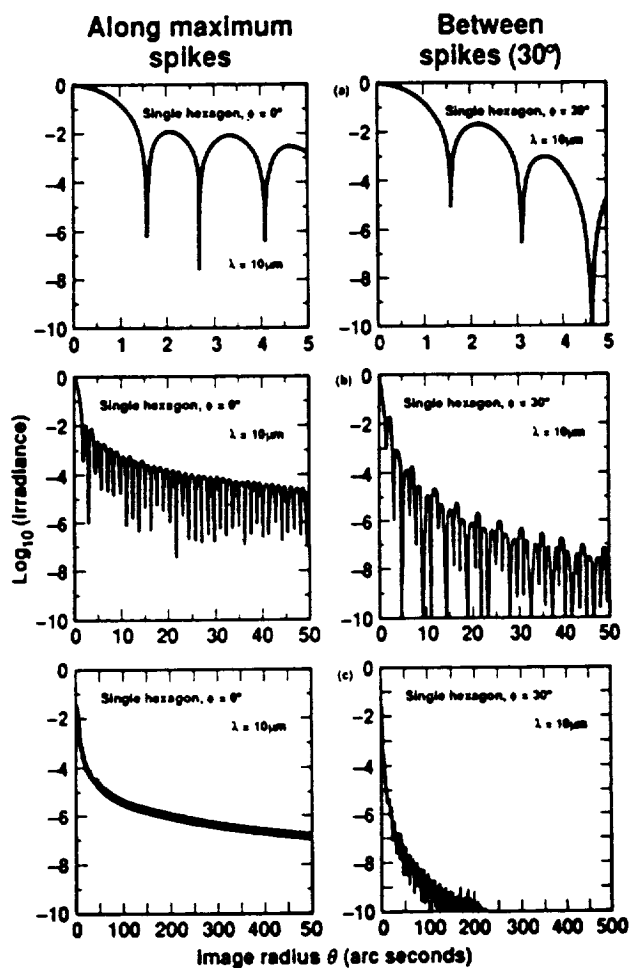


The function $1 - J_0^2(x) - J_1^2(x)$ representing the fraction of the total energy contained within circles of prescribed radii in the FRAUNHOFER diffraction pattern of a circular aperture.

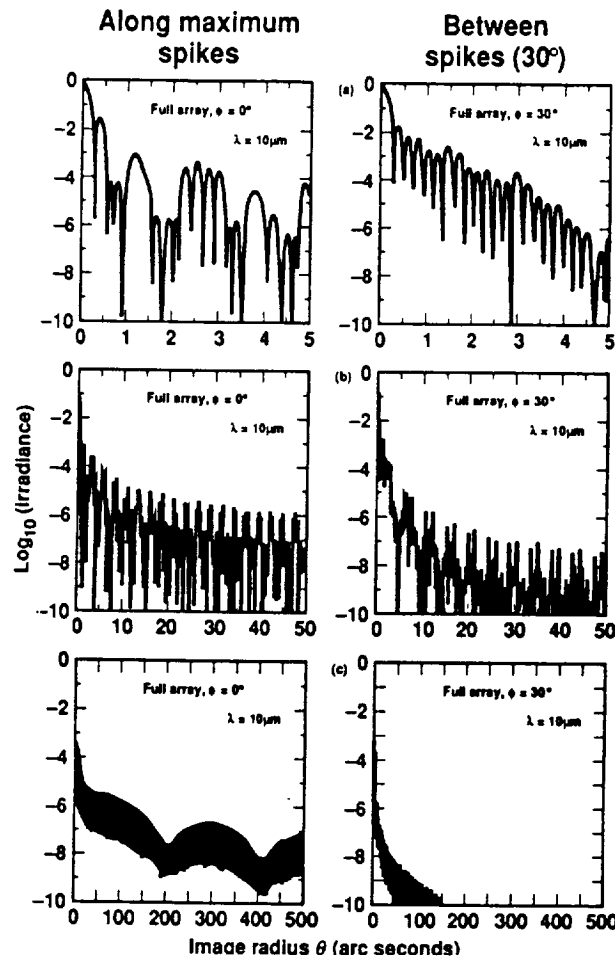
DIFFRACTION PATTERN FROM A SINGLE HEXAGONAL MIRROR



Single hexagon diffraction pattern at 10
micron wavelength (1.8-meter hexagons)



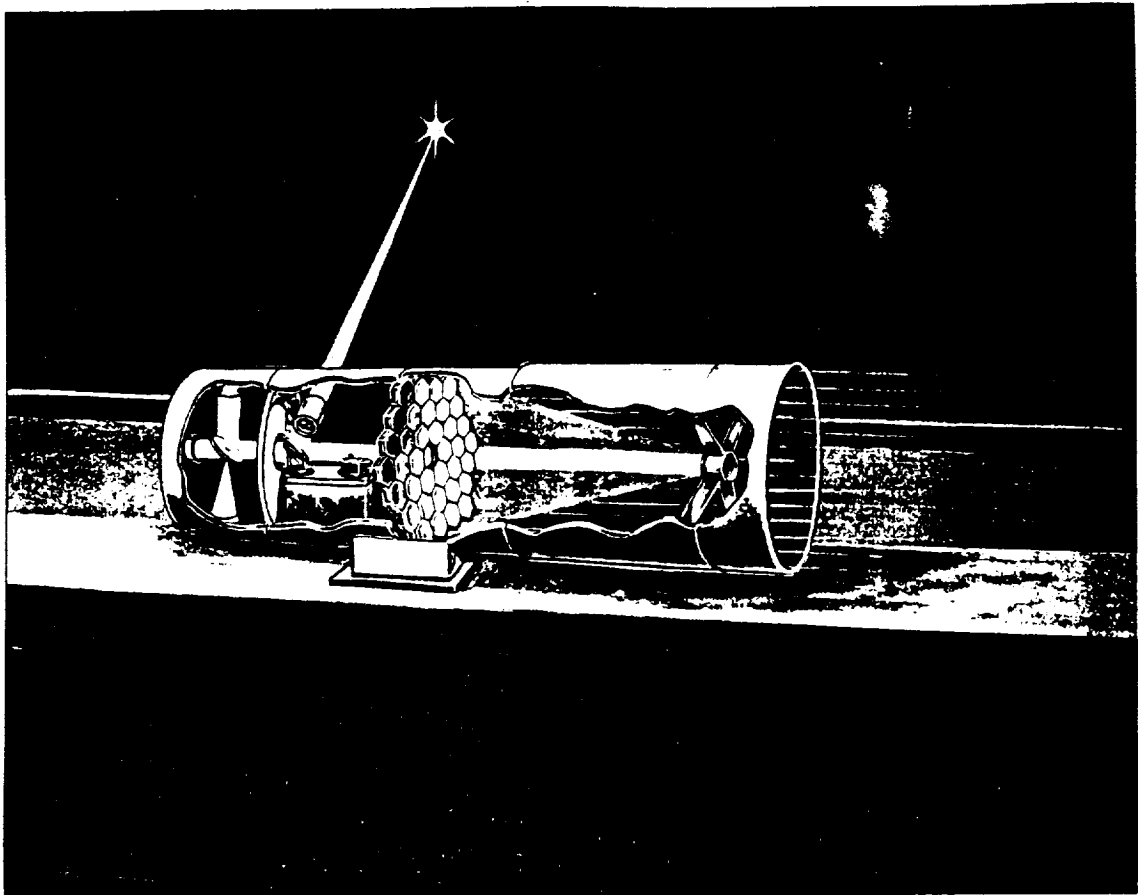
36-hexagon diffraction pattern at 10-micron wavelength (1.8-meter hexagon—10-meter full aperture)



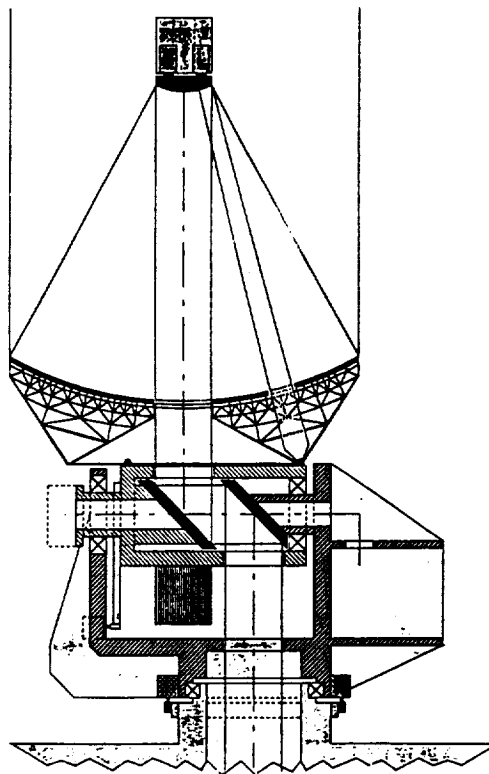
Effect of segmentation on aperture performance

- Strehl does not depend on segment number
- Strehl degradation depends on percentage area of gaps to total area:
 - Gap 1% of segment area \rightarrow Strehl = 96%
 - Gap 0.65% of segment area (Keck design) \rightarrow Strehl = 97.4%
- Variation in diffraction pattern at levels of 10^{-5} of peak and less and are present only many airy diameters away
- Details of energy distribution within the central lobe are unaffected by segmentation

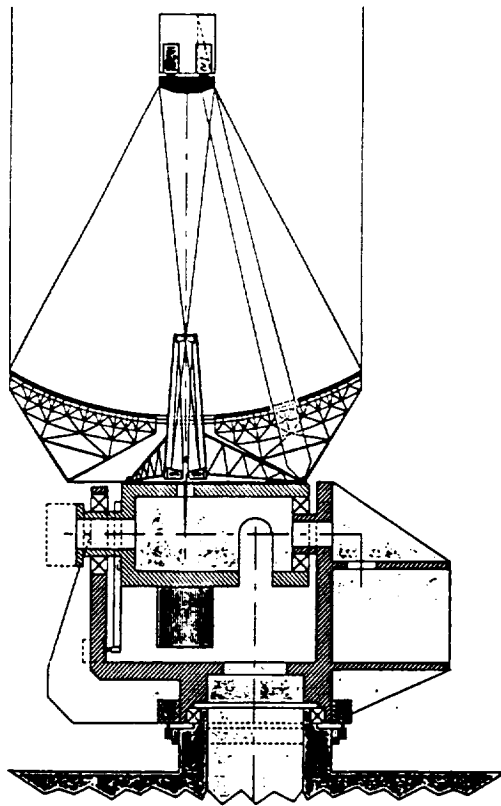
Imaging performance is not affected by segmentation



PAMELA Ground-based Laser Beam Director



ORIGINAL PAGE IS
OF POOR QUALITY

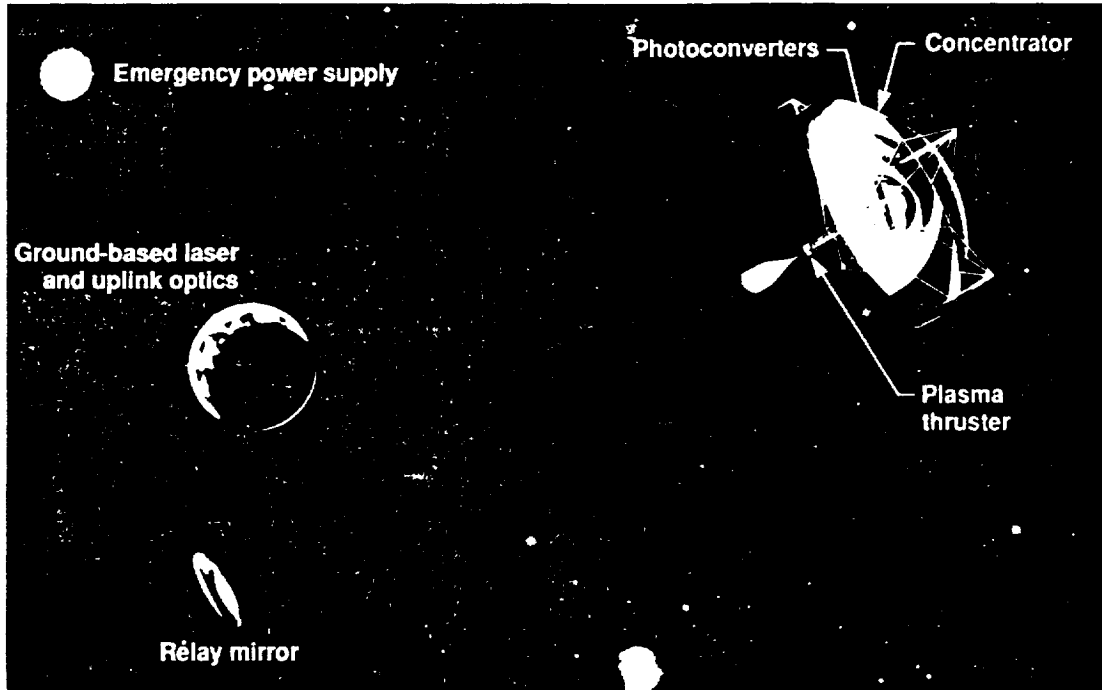


Technological goals of PAMELA-Type Optical System

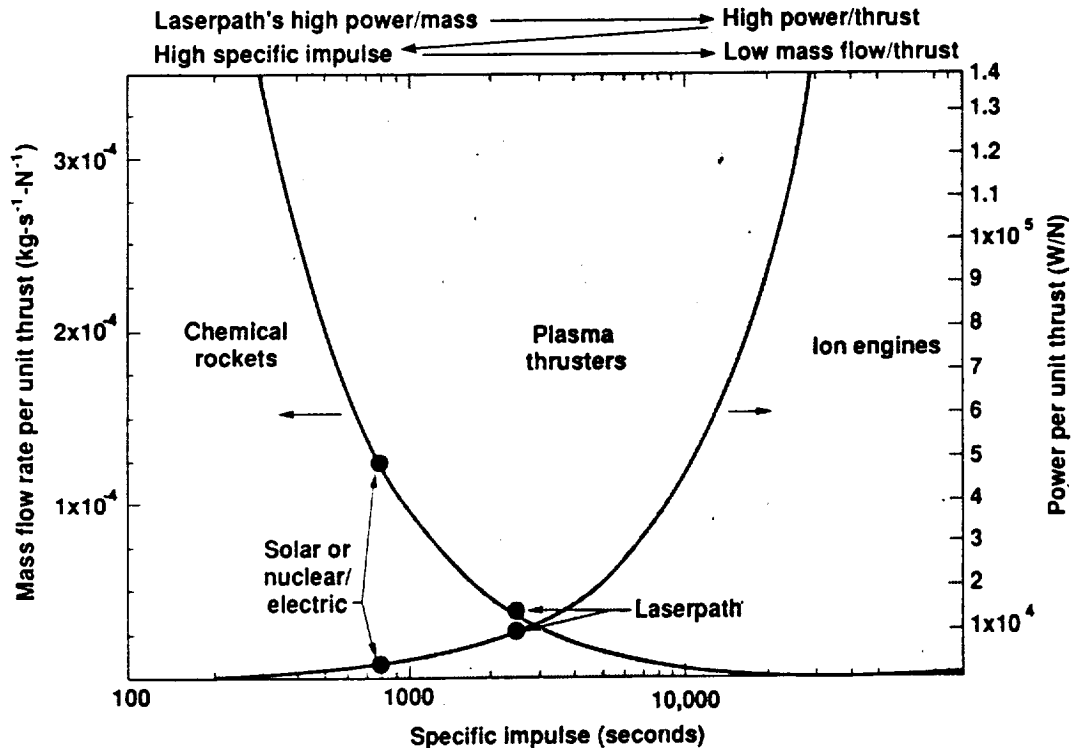
- Very large apertures (>10 m)
- Fast primary optic for a compact, lightweight telescope
- Compensation for internal optical aberrations
- Compensation for atmospheric turbulence
- Control architecture scalable to very large numbers of segments
- Elimination of the requirement to reconstruct wavefront phase from gradient measurements
- Large adaptive optics closed-loop bandwidth
- Diffraction-limited beam quality
- Identical intelligent mirror segments
- Identical wavefront sensor modules
- Economical fabrication through mass-production methods

Laserpath is a ground-based laser-driven space power and propulsion concept

A Laserpath manned lunar shuttle (MLS) departing for the moon

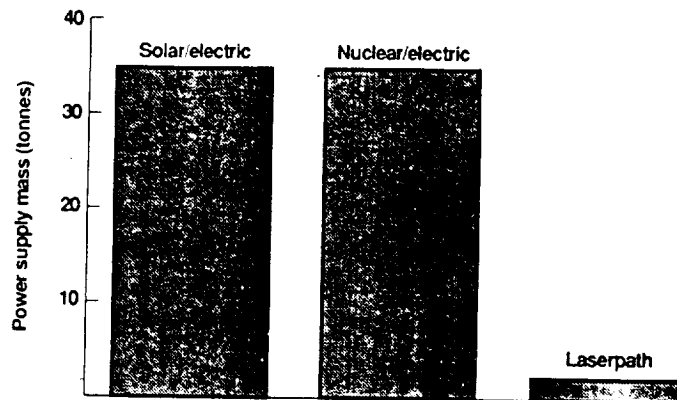


Because laserpath can exploit the high specific impulse of plasma thrusters, it requires little propellant mass



Laserpath's power supply mass is low in comparison with nuclear or solar vehicles for three reasons:

- The prime power source is not on board
- Monochromatic laser light is converted to electric power with high efficiency
- Pulse repetition rate matching of laser and plasma thrusters reduces need for on board power conditioning equipment



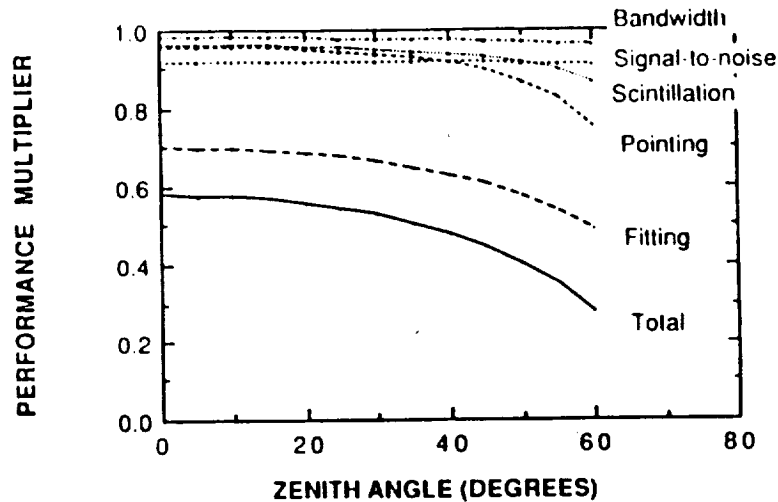
Shuttle rendezvous with tugboat in LEO. Residual shuttle main tank fuel is transferred to tug. Tug then boosts main tank or full shuttle payload to GEO

- $I_{sp} = 1,500$ seconds
- $\Delta V = 5,630$ meters/sec (each way)
- Tug spacecraft dry mass = 4,400 kg
- Available fuel mass = 3,640 kg*
- Main tank dry mass (or alt. payload) = 32,300 kg
- Total required energy = 4,500 GJ
- Minimum one way mission duration = 5.2 days
- Minimum required laser power = 10.2 MW

* 520 kg H_2 3, 120 kg LOX

ADAPTIVE OPTICS ERROR BUDGET

$\lambda = 1\mu\text{m}$, $r_o = 9.6\text{ cm}$ AND $\theta_o = 15\text{ }\mu\text{rad}$ AT ZENITH,
ACTUATOR SPACING 10cm, BANDWIDTH 100 Hz, WIND 6 m/s,
RETRO ARRAY AT MEAN POINT-AHEAD LOCATION



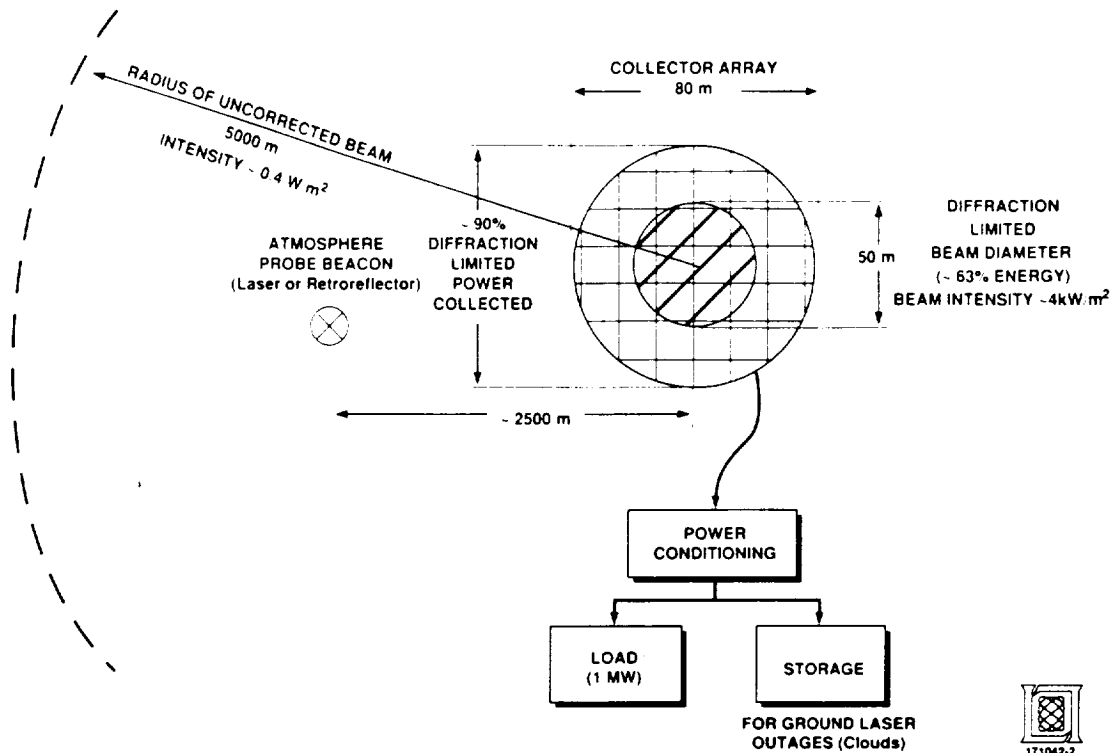
BASELINE SELENE POWER SYSTEM

REPRESENTATIVE POWER BUDGET

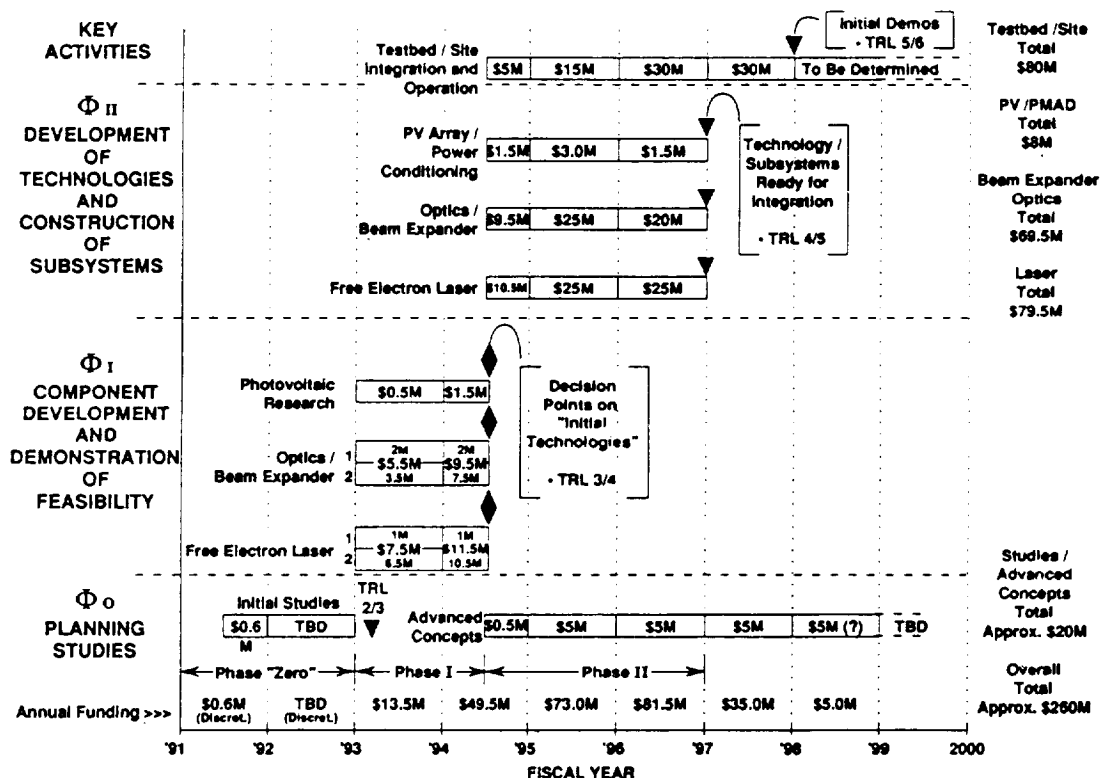
	POWER	EFF.
EARTH SITE POWER INPUT	110 MW	
LASER EFFICIENCY		0.1x
LASER OUTPUT	11 MW	
OPTICS TRANSMISSION		0.9
POWER OUT OF APERTURE	10 MW	
ATMOSPHERIC TRANSMISSION		0.9
ATMOSPHERIC COMPENSATION		0.5
COLLECTOR GEOM. EFFICIENCY		0.9
ARRAY ELECTRICAL EFFICIENCY		0.5
NET PV ARRAY ELECTRICAL POWER		
OUTPUT TO USER	2 MW	

A MINIMUM OF 3 EARTH STATIONS IS REQUIRED TO PROVIDE
CONTINUOUS 1+ MEGAWATT ELECTRICAL POWER TO USERS
ON MOON

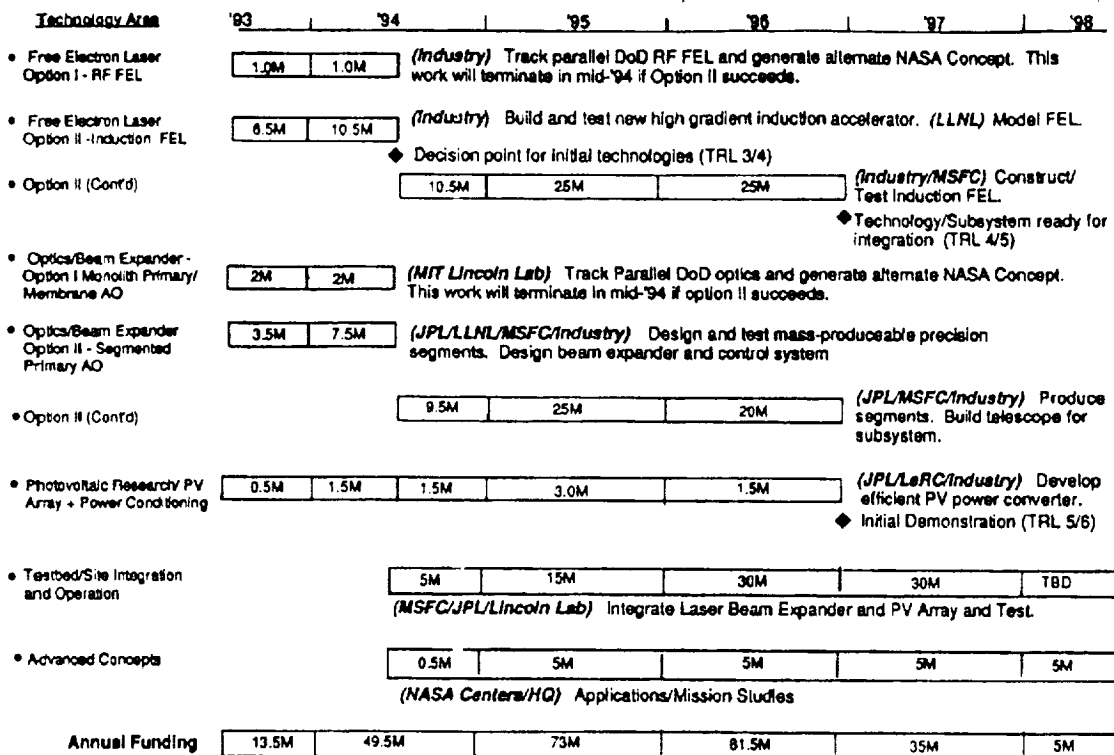
LUNAR STATION



PROJECT SELENE



LASER POWER BEAMING -- PROJECTION OF EXPENDITURES



LASER POWER BEAMING POWER AND PROPULSION FLIGHT DEMONSTRATION

- LASER-ELECTRIC PROPULSION VEHICLE FLIGHT FROM LOW EARTH ORBIT (LEO) TO LOW LUNAR ORBIT (LLO)
 - MISSION WOULD DEMONSTRATE/INVESTIGATE:
 - LASER POWER TRANSMISSION THROUGH ATMOSPHERE
 - TRACKING OF REMOTE TARGET BY TRANSMITTER AND RECEIVER
 - POWER CONVERSION BY PHOTOVOLTAIC ARRAY
 - RADIATION IMPACTS TO PV ARRAYS DUE TO TRANSFER THROUGH VAN ALLEN BELTS
 - ELECTRIC PROPULSION SYSTEM AS MISSION POWER LOAD
 - INTERACTIONS BETWEEN ELECTRIC PROPULSION SYSTEM AND PV ARRAYS
 - OTHER FEATURES OF THE DEMO MISSION:
 - OPERATE AT MODEST POWERS (10's OF kW TO MW)
 - INITIAL DEMO FROM LEO TO HIGH EARTH ORBIT (GEO ?) TO INVESTIGATE VAN ALLEN BELT IMPACTS CAN BE DONE WITH FIRST GENERATION SMALL TRANSMITTER MIRROR.
 - SECOND GENERATION LARGER TRANSMITTER USED FOR TRANSFER TO LLO

